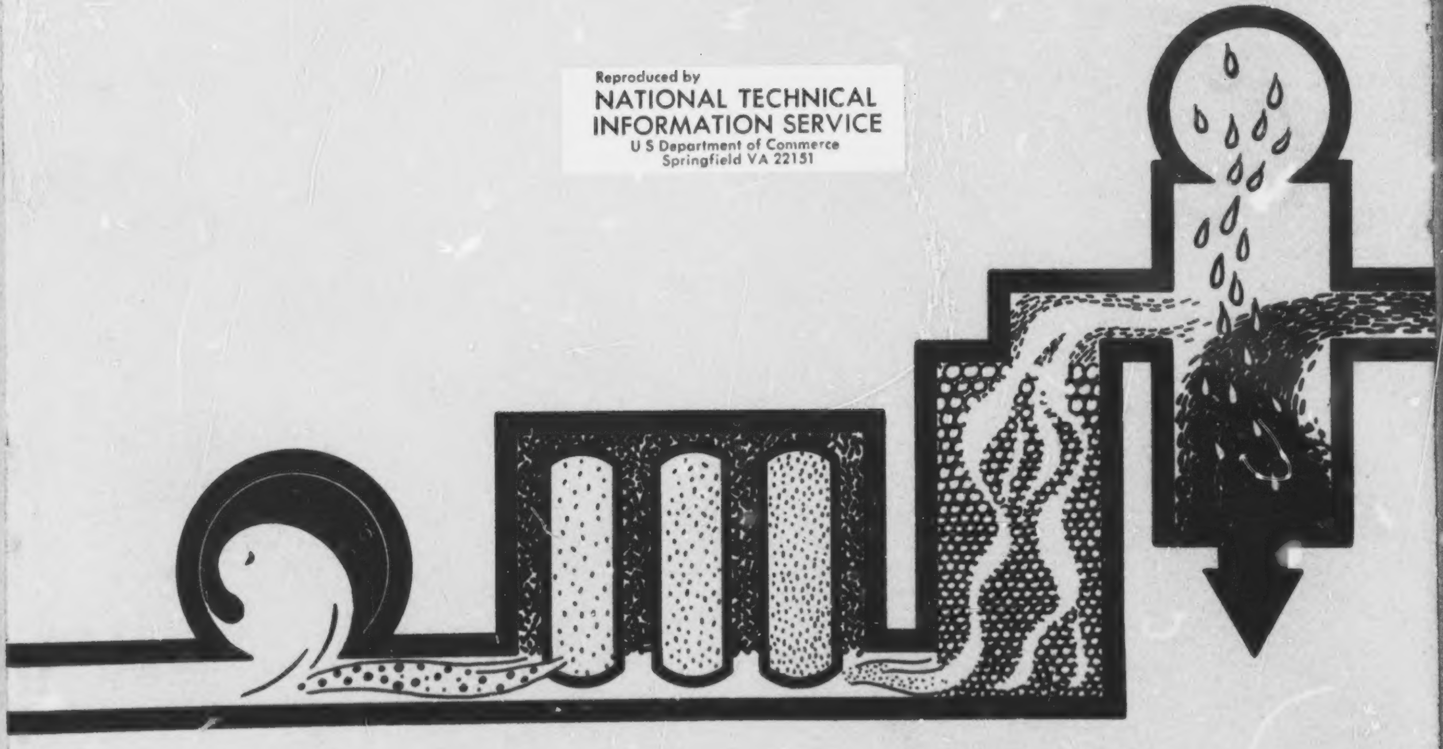
W72-13638

WATER POLLUTION CONTROL RESEARCH SERIES • 17050 DDY 12/71

PB 211 909

A LITERATURE SEARCH AND CRITICAL ANALYSIS OF BIOLOGICAL TRICKLING FILTER STUDIES-VOL. 1

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151



15.

U.S. ENVIRONMENTAL PROTECTION AGENCY

330

WATER POLLUTION CONTROL RESEARCH SERIES

The Water Pollution Control Research Series describes the results and progress in the control and abatement of pollution in our Nation's waters. They provide a central source of information on the research, development, and demonstration activities in the water research program of the Environmental Protection Agency, through in-house research and grants and contracts with Federal, state, and local agencies, research institutions, and industrial organizations.

Inquiries pertaining to Water Pollution Control Research Reports should be directed to the Chief, Publications Branch (Water), Research Information Division, R&M, Environmental Protection Agency, Washington, D. C. 20460

SELECTED WATER RESOURCES ABSTRACTS

INPUT TRANSACTION FORM

1. Report No.

2.

3. Accession No. **W** 72-13638

4. Title A LITERATURE SEARCH AND CRITICAL ANALYSIS OF BIOLOGICAL TRICKLING FILTER STUDIES-VOL.I,

5. Report Date

6.

8. Performing Organization Report No.

7. Author(s)

10. Project No. EPA Program 17050 DDY 12/71

9. Organization ~~The~~ Dow Chemical Company, Midland, Michigan, Functional Products and Systems Department.

11. Contract/Grant No.

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes Environmental Protection Agency, Water Pollution Control Research Series, ~~No. 17050 DDY~~, December 1971, 341 p, 8 fig, 6 tab.

In the report

16. Abstract A compilation, review and critique of the literature on biological trickling filter studies and related pollution abatement processes have been made. Volume I, the literature review and critical analysis, is divided into: (a) Introduction, Definitions, History and Background Theory of the Trickling Filter Process; (b) Plant Design, Materials of Construction, Operation, Maintenance and Performance; (c) Trickling Filter Research and Development Approaches, Ecology, and Patents, and (d) Applications of Trickling Filter to Specific Industrial Wastes. Based on the review, several general conclusions were drawn. There is no well-defined theory of design and operation. Much published work was redundant, and European efforts were not readily accepted in the United States, and vice versa. The literature reflects cycles of interest in trickling filters. The value of much of the early work was ignored. Solutions to complex pollution problems will be made by industry strongly supported by local, state and Federal governments. The filter will be used in high efficiency, modern wastewater treatment plants. The process is not applicable to all pollution problems, but its shock survival capabilities and rapid flow-through time are definite advantages which cannot be overlooked in any design of a waste treatment facility. (Galwardi-Texas)

(See also W72-13639)

17a. Descriptors *Trickling filters, *Bibliographies, *Biological treatment, Aerobic treatment, Filters, Treatment facilities, Industrial wastes, Municipal wastes, Theoretical analysis, Construction, Operation and Maintenance, ~~Performance, Research and development,~~ Patents, Pollution abatement, *Waste water treatment, Chemical wastes, Pulp and paper industry, Radioactive wastes

17b. Identifiers Biological filters, Biofilters, Percolating filters, Sprinkling filters, Brewery and distillary wastes, Gas and coke plant wastes, Food processing wastes, Institutional and military wastes, Milk processing wastes, Pharmaceutical wastes, Meat and poultry wastes, Tannery and textile wastes, Metal working and production wastes

17c. COWRR Field & Group 05D, 10A, 10F

Copy available from GPO Sup Doc EP2.10 17050 ~~as~~ DDY 12/71, $2.50; microfiche from NTIS as PB 211 909, $0.95.

18. Availability ✓

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

Abstractor Ed Galwardi

Institution Texas Univ, Austin

WRSIC 102 (REV. JUNE 1971)

VOLUME I

A LITERATURE SEARCH AND CRITICAL ANALYSIS OF BIOLOGICAL TRICKLING FILTER STUDIES

by

Functional Products and Systems Department
The Dow Chemical Company
Midland, Michigan 48640

for the

Office of Research and Monitoring

ENVIRONMENTAL PROTECTION AGENCY

Project No. 17050 DDY
Contract No. 14-12-474

December 1971

ib

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402 - Price $2.50

ABSTRACT

A compilation of the literature on biological trickling filter studies and related pollution abatement processes was made. References were selected for a section of the review and then critiqued.

The review is composed of two volumes. Volume I, the literature review and critical analysis, is comprised of four parts: (a) Introduction, Definitions, History and Background Theory of the Trickling Filter Process; (b) Plant Design, Materials of Construction, Operation, Maintenance and Performance; (c) Trickling Filter Research and Development Approaches, Ecology, and Patents, and (d) Applications of Trickling Filters to Specific Industrial Wastes. Volume II is the bibliography, a compilation of over 5,000 references in author and journal alphabetical sequence.

Based on the review, several general conclusions were drawn. There is no well-defined theory of design and operation generally accepted by the principal investigators in the field. A great amount of published work was redundant, and European efforts were not readily accepted in the United States, and vice versa. The literature reflects cycles of interest in trickling filters. The value of much of the early work was ignored. Solutions to complex pollution problems will be made by industry with strong urging and support from local, state, and Federal governments. The biological trickling filter will be used in high efficiency, modern wastewater treatment plants. The process is not applicable to all pollution problems, but its shock survival capabilities and rapid flow-through time are definite advantages which cannot be overlooked in any design of a waste treatment facility.

This report was submitted in fulfillment of Project Number 17050 DDY, Contract 14-12-474, under sponsorship of the Environmental Protection Agency.

CONTENTS

Section Page

I Conclusions and Analysis 1
II Summary of Review 5
III Introduction 11

Part I

IV Introduction 15
V Definitions 19
VI Historical Development 23
VII Background Theory of Process 27

Part II

VIII Design Criteria of Various Trickling Filter Modifications 47
IX Construction Trends 123
X Operation of Trickling Filters 155
XI Maintenance of Biological Trickling Filters 163
XII Performance Summary of Trickling Filters 173

Part III

XIII Laboratory-Scale Investigations 195
XIV Pilot-Scale Investigations 201
XV Field- and Full-Scale Investigations 207
XVI Ecology 213
XVII Patents 221

Part IV

XVIII Brewery and Distillery Wastes 225
XIX Organic and Inorganic Chemical Wastes 233
XX Gas and Coke Plant Wastes 241
XXI Food Processing Wastes 251
XXII Institutional and Military Wastes 263
XXIII Laundry and Cleaning Wastes 273
XXIV Meat and Poultry Wastes 279
XXV Metal Working Wastes 289
XXVI Milk Wastes 295
XXVII Pharmaceutical and Fermentation Wastes 301
XXVIII Pulp and Paper Wastes 309
XXIX Radioactive Wastes 321
XXX Tannery Wastes 327
XXXI Textile Wastes 333
XXXII Acknowledgements 341

Preceding page blank

FIGURES

		PAGE
1	SCHEMATIC DIAGRAM OF TRICKLING FILTER PROCESS	17
2	FACTORS INFLUENCING THE USE OF TRICKLING FILTERS	25
3	SCHEMATIC OF THEORY	29
4	BIOFILTRATION RECIRCULATION DIAGRAMS	90
5	FLOW DIAGRAMS OF SINGLE STAGE HIGH-RATE FILTRATION	91
6	FLOW DIAGRAMS OF TWO-STAGE HIGH-RATE FILTRATION	92
7	CONSTRUCTION COST PER CAPITA FOR TRICKLING FILTERS	118
8	CONSTRUCTION COSTS PER CAPITA FOR IMHOFF SLUDGE DIGESTION PLANTS	119

TABLES

No.		Page
1	Design Comparison of Different Rate Filters	55
2	Depth of Medium Trends	85
3	Characteristics of Types of Filter Media (5196)	149
4	Treatment Operational Costs of Sewage Plants	161
5	Summary of Filter Criteria	186
6	Composite List of Trickling Filter Organisms - Cooke (779)	214

SECTION I

CONCLUSIONS AND ANALYSIS

The following conclusions and analysis are derived from the review of the literature on biological trickling filter studies.

1. Several theories are proposed to describe the performance of biological trickling filters. Yet in the ninety years of development, there is no generally accepted theory.

2. Recent publications demonstrate in-depth understanding of specific phases of the mechanisms involved in biological filtration.

3. A lack of appreciation of ecological information is noted by many workers who regard the trickling filter process as a "black box" in which the identity of responsible organisms is unimportant, and only the overall performance of the process is evaluated.

4. Intermittent dosing at low hydraulic rates is generally replaced by continuous dosage at high rates which involves design changes to assure an acceptable effluent.

5. The contact time or retention time is significant, and greater removal is achieved by having an interface of active organisms, pretreated wastes and sufficient oxygen for an optimum time interval.

6. Little conclusive evidence is available which illustrates inherent advantages of one medium over another, provided these media conform closely to ideal medium requirements. However, some porous materials adsorb certain organics and radioisotopes to a limited extent.

7. Natural ventilation is adequate for most waste treatment conditions. With elevated temperature and high organic loadings, forced air ventilation is required, but an oxygen-enriched atmosphere is seldom, if ever, used for ventilation.

8. Evidence indicates that the temperature of the waste, not of the air, is significant in determining the performance of biological filtration.

9. Controversy exists over the effects of recirculation, and recent reports indicate that (a) recirculation of settled sludge is detrimental, (b) recirculation of clarified effluent is advantageous to filter performance, and (c) intermediate clarification between two-stage filtration is not necessary.

10. Trickling filters are used successfully in series operation with other units such as septic tanks and the activated-sludge process. In the case of the latter, high-rate filters are effective prior to activated-sludge treatment and low-rate filters are effective after activated-sludge treatment.

11. The terminology for the units for performance evaluation certainly can be improved, since percent BOD removal (commonly used) does not express the actual pollution load to a receiving body, nor is it easily correlated with operating expenses reported in dollars/mgd.

12. In-depth mathematical investigations have the tendency of losing their usefulness to the nonmathematically oriented practitioner, and it is unfortunate that these valuable studies have not been correlated with the vast operator experience available.

13. Data derived from laboratory-scale investigations are used conservatively to define pilot plant conditions, but are adaptable, with the proper interpretation, to full-scale designs.

14. Pilot-scale investigations are used for research and development purposes as well as definition of design criteria. An unfortunate temptation must be noted, for this scale study is a means of delaying the time of construction of full-scale facilities.

15. Engineers place more confidence on field- or full-scale investigations and relationships derived therefrom than on laboratory data, with the recognized limitations of uncontrollable environmental conditions, variable waste sources, and problems in sampling, analyzing and interpreting the data.

16. Many industrial wastes are at least partially treated by biological filtration with most influents requiring some form of pretreatment to remove suspended solids, adjust pH, equalize temperature and shock loads, and maintain a continuous flow. The ability of biological trickling filters to survive temporary changes due to fluctuating characteristics of industrial wastes, even after pretreatment, is of considerable value.

17. Architectural considerations do not govern trickling filter plant design in this country, but indications of an awareness that this is desirable are encouraging.

18. It is observed that proper operation by qualified personnel is imperative to assure that a biological filtration plant will perform as designed and constructed.

19. For a biological filtration plant to be nuisance-free, the primary maintenance duty is simply cleanliness. Several approaches using physical, chemical, and biological means for the control of filter flies are suggested, with the biological scheme to be preferred.

20. A point of interest for future design may be gathered from the many papers criticizing old waste treatment plants which do not have facilities for nutrient removal. However, at the time of their design, the purpose of their construction was disease prevention and control of water-borne epidemics. Present and future designs should, whenever possible, project the possibility of additions to treatment facilities.

21. The literature reflects competition or a lack of confidence among nations which results in conflicting conclusions and duplicated efforts, but also produces alternative solutions to waste treatment problems.

22. The several trade waste associations and committees of founder societies are dedicated to the dissemination, sponsorship, and evaluation of work on waste water. These groups have made major contributions to the characterization of various waste waters with suggested methods of treatment. This is an excellent example of cooperation to solve complex problems.

23. This review is not intended as an in-depth patent search, but sufficient evidence is gathered in the areas investigated to result in the citation of some issued patents.

24. Cost comparison data are difficult to obtain, and quite often the information is reported in a nonstandard form, further complicating the economic evaluation of the processes.

25. A significant lesson in design, as it affects the total economy, appears available based on the experiences during World War II. Under the pressures of war, treatment plants were intentionally designed to accomplish just adequate treatment, and, as populations become more dense and these plants were modified, further complications developed in operation and conversion, and added expenses were incurred to correct early designs.

26. The literature is highly redundant; for example, reports on the construction of a waste treatment facility are published in several trade journals. Many conflicting viewpoints are also expressed, seemingly unaware of the work of other investigators.

27. Examples of rediscovery are noted, such as the use of dipping contact filters, with little or no evidence that modifications have been made to correct the errors of the past which caused the earlier work to fade in popularity.

28. The apparent lack of discretion by authors to clutter the literature with similar, if not identical, publications cannot be overemphasized. Under the title of "Solve All Problems" -type papers, several people published rather weakly documented investigations with only tacit applicability to the solution of waste treatment problems.

29. It is observed that cycles of interest in biological trickling filters are experienced in about fifteen-year increments, beginning shortly before 1900.

30. Generally, the biological trickling filter has been, is, and will be used for a considerable period of time. All facets are not understood, but sufficient experience has been gained which allows this process to be used effectively in conjunction with other waste treatment operations. The process is obviously not applicable to all waste problems, but many investigators outline, in hundreds of pages, the advantages and illustrate the cases where the biological trickling filter provides the treatment required.

SECTION II

SUMMARY OF REVIEW

In describing the literature on trickling filters, E. Sherman Chase (658)* stated, "Over the years much has been written upon trickling filters. A review of the literature shows that the same thing has been said over and over." With few exceptions, Mr. Chase's statements, based on 35 years of experience and written 26 years ago, are still applicable today.

The purpose of the present effort was established upon a recognized need to review and critique the literature of the biological trickling filter. Engineers and scientists must have available information to aid in documenting their conclusions, to draw upon the experience of the past, to educate the novice, to avoid unintentional duplication of work, and to keep abreast of developments.

The approach involved a compilation of references which were then categorized. Major areas of interest were outlined. The categories were matched and blended to produce sections covering specific topics in the major areas. The result of this effort facilitated a composite of many of the references on a subject. References were selected, reviewed and critiqued (Volume I). The bibliography (Volume II) is organized in author and journal alphabetical sequence.

General information on definition of the biological trickling filter process is followed by a discussion of the history and background theory. This information provides a basis for the discussion of the remainder of the text. The text is prepared in four parts, i.e., Part I - Introduction, Definitions, History and Background Theory of The Trickling Filter Process; Part II - Plant Design, Materials of Construction, Operation, Maintenance and Performance; Part III - Trickling Filter Research and Development Approaches, Ecology, and Patents; and Part IV - Applications of Trickling Filters to Specific Industrial Wastes.

Theoretical investigations deal with the effect of suspended solids, the hydraulic and organic loadings, and rates of recirculation applied to biological trickling filters. Theoretical criteria are developed on the chemical and mechanical properties of the required trickling filter medium. Several investigators developed a lively dialogue on various theories of natural and forced ventilation for the biological trickling filter. Mathematical investigations are noted to predominate in the literature of the last decade as attempts were made to put the various theories of biological filtration on a quantitative basis.

---

*References are found in Volume II.

In the discussion of design factors, the type of waste is identified as the principal criterion to be considered for the application of biological filtration. Several modifications of the trickling filter have been designed, such as contact and dipping contact beds, prior to the conventional form of low-rate and high-rate trickling filters operating in single- and two-stage systems. Multi-unit systems employing biological filtration in series with the activated-sludge process, lagoons, septic tanks, Imhoff tanks, and other unit operations are reported with their inherent advantages and disadvantages. Modifications of the basic process, such as three-stage biological filtration, alternating double filtration and contact aerators, have application under specific circumstances. Design criteria for roughing and polishing filters are well established and developed for biologically generated solids separation and disposal, as well as effluent disposal through reuse. Design information related to recirculation is shown to have attracted the attention of the mathematically oriented investigators who developed expressions relating the hydraulic and organic load and their effect on the filter.

Pretreatment systems have been designed principally for conditioning the influent to the filter by removing most of the suspended material, providing a neutral pH, an ambient temperature, and an equalized flow. Post-treatment applications have been designed primarily for the solids-liquid separation and disinfection, as well as some nutrient removal to provide an acceptable effluent. Design factors for the ventilation and underdrainage systems and filter enclosures involved detailed studies of the temperature effect, ventilation rate, oxygen content, carbon dioxide content, and nuisance control, among other factors. Economic considerations of design deal with capital cost versus operational cost, with limited data available.

Construction trends in waste treatment plants are summarized by characteristics developed over several decades. Construction of package plant installations has a practical application, and data on their successful operation are available. Materials of construction for distribution, biological film, support media, walls, and enclosures plus other appurtenances are discussed in considerable detail. Construction practices in the economic use of local materials for enclosures, media and underdrains are also reported. Architectural considerations for waste treatment plant construction are not emphasized to any extent in the literature.

Proper operation of biological trickling filter plants is of utmost importance. The best designed plant, constructed to exact specifications, can still produce poor quality effluent, if operated improperly. Many problems, such as filtration start-up, are adequately solved through good communication among operators of treatment plants. Operator training was of sufficient interest that information was published dealing with the requirements of properly trained individuals, licensing these individuals, as well as establishing a wage scale. Operational costs are reported frequently prior to World War II, but later cost data are only available to a limited extent.

Maintenance has become a major factor in conjunction with the design and operation of biological trickling filters. As wages increase, man-hours of maintenance will be decreased. Information dealing with maintenance and the development of maintenance-free equipment occurs intermittently throughout the literature. The use of corrosion-resistant materials is encouraged, and access to the equipment for maintenance is incorporated in the design. The avoidance of nuisance conditions of odors, filter fly production, and other objectionable conditions occupies a considerable volume of the literature.

In an attempt to evaluate the performance of biological filtration processes, many investigators developed design expressions and mathematical models. More data were available to investigators after the National Research Council's studies in the late 1940's. With these data and the model described by the Council, several investigators proposed alternative relationships involving various parameters. An appreciation for statistics was demonstrated, and monographs were developed for the rapid solution of many of the derived expressions. The determination of the key parameters defining biological filtration performance evoked considerable debate among investigators. Other filter performance criteria were expressed in terms of bacterial removal, viral removal, and disease prevention. Explanations of the performance of biological filters in relation to these factors were published and data indicating the limitations of the process are available.

The results of research and development, using the laboratory-scale biological trickling filter simulation, either in a miniature filter configuration or by modeling some aspect of the filtration phenomenon, are extensively reported. Aside from the economy, certain environmental factors can be controlled by testing at this scale, thereby simplifying performance changes with defined variables. Laboratory simulations, such as inclined flat planes, rotating tubes, vertically suspended spheres, as well as other devices, were used to develop rational formulas to describe the performance of the biological trickling filter. Laboratory-scale research and development are frequently used to study and measure significant variables from which a pilot plant can be constructed, leading to the development of design criteria for full-scale operation. With proper interpretation of the data, designs have been made for full-scale installations basedon laboratory-scale experimentation.

Pilot plants have been investigated, with or without preliminary laboratory studies, primarily for the development of design criteria for full-scale installations. The results from pilot plant operation have been compared with data from theory developed in the laboratory. Pilot plants have been used extensively by several interested groups, such as regulatory agencies, industry, and consulting engineers, to develop efficient waste treatment facilities. If design changes were required, considerable savings were obtained at the pilot plant-scale which would not be feasible under full-scale conditions nor meaningful under laboratory-scale conditions.

Many contributors emphasized that field- and full-scale investigations are the most desirable scale for testing and development. Very high credibility was given to relationships developed from those data. The investigators demonstrated an awareness of the limitations of full-scale operations, such as the expense involved, the duration of study, and the inability to establish key parameters under controlled conditions. The conservative approach to research and development has been to use limited laboratory investigations to define performance characteristics, extensive pilot plant investigations to define design criteria, and full-scale construction and operation evaluations to determine efficiencies and required modifications.

Various life forms have been regarded as important in the function of biological trickling filters. The required environmental conditions for the filter biota were noted, along with observed organism stratification throughout the depth of the biological filter. Frequent ecological investigations were reported by regulatory agencies, design engineers, and operators for upgrading the performance of waste treatment plants, detecting malfunction, and indicating the type of correction which should be instituted. Occasional reference was made to the use of fungi for specific waste treatment, but the usual reference dealt with control by physical, chemical, and biological means.

The interrelationships among algae, bacteria, fungi, protozoa, insect larvae, worms, nematodes, rotifiers, and other organisms were reviewed in several accounts. Many cases were cited of ecological upset when one life form predominated and usually resulted in a nuisance condition or a loss of plant efficiency. In an effort to increase treatment plant efficiencies, pure culture was used in the waste treatment, but the results showed no advantages.

The results of research and development were the many patents in the area of biological filtration, distribution devices, filter media, ventilation and odor control systems, post-treatment devices, trickling filters in combination with other processes, unique cleaning and maintenance procedures, and other similar categories.

Several specific industrial wastes treated by biological filtration with various degrees of efficiency were reviewed and categorized, such as brewery and distillery, chemical production, coke and gas plants, food processing, military and institutional, laundry and cleaning, meat packing and poultry, milk processing, pharmaceutical and fermentation, pulp and paper, radioactive, tannery, and textile wastes. Most of the industrial wastes required considerable pretreatment to guarantee efficient biological filtration. Quite often combined units such as the trickling filter with the activated-sludge process gave the most efficient and reliable treatment.

Prior to 1930, there was considerable interest expressed by the investigators in treating various trade wastes admixed with domestic sewage, but considerable difficulty was encountered. In the post-World War II period, with the advent of high-rate biological filtration, successful treatment of many of the more difficult trade wastes was accomplished in combination with domestic sewage treatment. Biological filtration was shown to have a definite part in the treatment of industrial wastes, but was not a cure-all, as other systems possessed advantages under specific conditions. General conclusions and recommendations were made based upon the reviewed publications. These conclusions dealt with the quality of the publications, significant points of agreement and disagreement, and interpretation of information in the reviewed material.

SECTION III

INTRODUCTION

The conscientious efforts of many thousand people working on biological trickling filters at the laboratory, pilot plant and field scales, along with the subsequent reporting of the results, have created a problem -- a tremendous volume of information. To delve into the background literature requires considerable time and effort and is not always practical or feasible. To bridge the gap of the unavailability of disseminated information to the novice, practicing engineer or environmentalist, all of these data should be collected, compiled and evaluated in one source. Thus, this literature review and critical analysis were undertaken in an attempt to provide a source of trickling filter information to all technically interested individuals in this rapidly expanding field.

It was the intent of this project to assemble, compile, and categorize the international literature pertaining to the biological trickling filter, and then review and critique this comprehensive documentation. Constructive criticism included the strength as well as the weakness of the information. Careful attention was given to the intent and purpose of the investigations. Selection of the articles reviewed was based upon their timeliness and technical excellence. It was found that many articles were similar; for this review, representative papers were selected and the others listed as additional references.

This literature review covers the period from the earliest beginning of the concept of the trickling filter through 1968. The primary sources of information were the Chemical Abstracts and the Water Pollution Abstracts. These sources indicated the original articles in the trade journals, and many of these were reviewed and, if sufficiently important, obtained for the reference file. Government publications were another valuable source of pertinent information. The personal reference files of certain members of the technical staff of The Dow Chemical Company, Midland, Michigan, with background in waste disposal and trickling filters, were the beginning of this compilation of references.

A review of the collected information developed a list of over 600 key words. By using the key words and numbered references with a computer, the references to specific topics were located and sorted out, and the sections written with the literature and literature abstracts on hand.

The review and critique are comprised of two volumes. Volume I is the literature review and critical analysis of selected articles. After the summary and general conclusions, Volume I is organized in four technical parts, i.e., Part I - Intro-

Preceding page blank

duction, Definitions, History and Background Theory of the Trickling Filter Process; Part II - Plant Design, Materials of Construction, Operation, Maintenance, and Performance; Part III - Trickling Filter Research and Development Approaches, Ecology, and Patents; and Part IV - Applications of Trickling Filters to Specific Industrial Wastes.

Volume II is the bibliography of 5,665 quoted and additional references in alphabetical sequence. The reference numbers are enclosed by parentheses in the text of Volume I.

PART I

INTRODUCTION, DEFINITIONS, HISTORY AND BACKGROUND THEORY OF THE TRICKLING FILTER PROCESS

Part I of this review establishes a background on the subject of biological trickling filters. After a brief introduction of waste treatment, a simplified explanation of the trickling filter process is given. The applications of trickling filters are considered, along with the definitions used in the literature and in the text. The history and development of the trickling filter process are followed by the development of the theory of the process. This introductory background defines the scope of the various factors which affect the biological trickling filter.

SECTION IV

INTRODUCTION

At the risk of over-simplification, the biological trickling filter process may be described as follows: The sewage is distributed over a suitable solid supporting structure. As the waste stream falls, intimate mixing of the air, the waste stream, and a microbial population (which is attached to the supporting structure) results in an aerobic biochemical reaction, reducing the organic waste. The trickling filter is most commonly used after primary sedimentation has removed settleable solids. Non-settleable solids and soluble organic material are removed by an adsorption-oxidation phenomenon occurring at the biofilm-waste stream interface. The effluent from the trickling filter usually contains solids which are generated by periodic or continuous sloughing of the biological film from the filter medium which was developed during the aerobic oxidation. The effluent is then subjected to further clarification, or other processes, which will handle the solid-liquid separation.

The number of trickling filter installations in the United States exceeds 4,500. Dosage rates may be from 25 to more than 9,000 gal./ft^2/day, with organic loads from 5 to 1,512 lb BOD/1,000 ft^3/day. A major factor in developing the popularity of trickling filters was the necessity for sewage treatment by rapidly expanding population centers during World War II (1151, 1563, 1564, 2508, 4015). The war effort required a reliable, low cost, temporary treatment system at many military installations. This demand was enough to motivate the designers and developers to specify and use the high-rate systems and thereby lay the bases for contemporary developments. These developments are in the form of multi-stage, deep-bed operations using various media and high continuous hydraulic loading.

DESCRIPTION OF THE PROCESS

The trickling filter process has been described by many authors (112, 288, 1826, 2984, 3327). In the strictest sense, the term, trickling filter, has been considered a misnomer (134, 2504, 2756, 4537) because it does not act as a mechanical filter, similar to sand filters, for the removal of suspended material. However, removal of organic contaminants does occur by the action of the microbial slime or the biofilm. This process takes advantage of the microorganisms present in the waste and the environment which, when mixed with the proper nutrients (waste stream) and sufficient air, will develop a slime layer which adheres to a supporting structure. This structure has been, traditionally, a type of crushed inorganic or other inert fabricated material. The waste stream is normally distributed from the top and allowed to trickle down through the supporting material. As the biological mass forms on this support, additional nutrients are required which are

Preceding page blank

obtained from the waste stream being treated. The normal life functions of respiration and synthesis of the organisms convert the polluting materials to carbon dioxide and water with the development of additional cell mass (biofilm or sludge). Periodically, the cell mass or sludge detaches or sloughs from the supporting medium and is separated from the waste stream in a subsequent clarifier. The generalized biochemical reaction occurring in the filter is oxidation, and may be represented as:

$$(\text{Organics}) + (\text{Air}) + (\text{Biofilm}) \xrightarrow{\text{Effluent}} (\text{Need Clarifier}) + \begin{array}{l}\text{Residual}\\ \text{Organics}\\ \text{and}\\ \text{Inorganics}\end{array}$$

$$\text{CHONSP} + O_2 + \text{Cells} \xrightarrow{H_2O} \text{More Cells} + NO_3^- + CO_2 + H_2O + \begin{array}{l}\text{Oxidized}\\ \text{Byproducts}\end{array}$$

The design, control, and operation of this seemingly straightforward method of treatment have occupied sanitary engineers and interested scientists for over 90 years. There have been many types and arrangements of systems proposed, constructed, and operated (and some discarded) for the distribution, reaction, and collection of the waste stream in the evolution of an efficient biological reactor. The relationships of the supporting medium, the biological film, the waste stream, and the atmosphere, as illustrated in Figure 1 (3917), have challenged the mathematical skill of engineers and scientists for many years. Design equations and formulations are currently being proposed to explain some of these relationships.

APPLICABILITY OF THE PROCESS

The application of the trickling filter to wastewater treatment has been found profitable in areas where: (a) personnel may be limited (2204), (b) small flows exist, (c) an effluent of from 20 to 30 mg/l of BOD is acceptable, (d) partial treatment is required in a multi-stage process, (e) land area requirements dictate height to be increased to achieve the designed reaction volume, (f) intermittent discharges of toxic or inhibitory waste create shock conditions, and (g) a specific treatment may be made on an industrial waste.

Besselièvre (308) and Hoak (1964), as well as others, have reported successful use of trickling filters on industrial wastes, such as pharmaceutical, radioactive, high carbohydrate such as that found in beet sugar plants, and brewery wastes. Wastes occurring as a byproduct of coke, food processing, chemical industries (2351), distilleries, meat packing, pulp and paper mill, laundry, petrochemical and petroleum, poultry processing, textile, tannery, and many others have also been treated by this method. The ability of the trickling filter to sustain itself during temporary changes in temperature, or organic content, or toxicity of the influent has made it a valuable process in industrial waste treatment. The trickling filter was frequently used in the treatment of military waste (5590), as well as the more conventional application for treating municipal waste (1826, 4916).

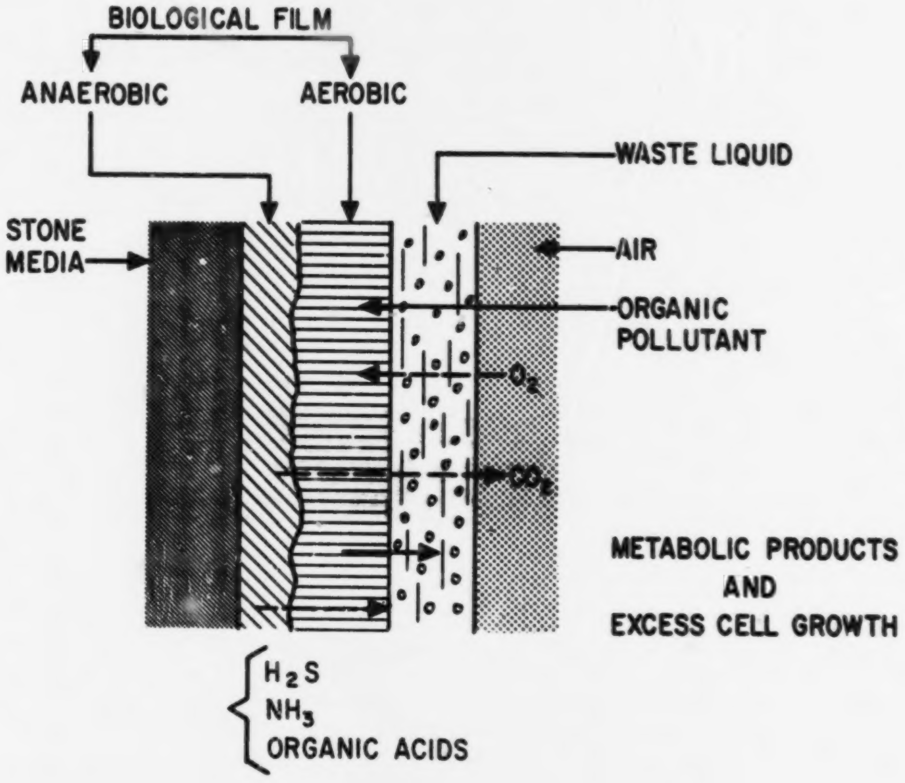

BIOLOGICAL FILM
ANAEROBIC
AEROBIC
WASTE LIQUID
STONE MEDIA
AIR
ORGANIC POLLUTANT
O_2
CO_2
METABOLIC PRODUCTS AND EXCESS CELL GROWTH
H_2S
NH_3
ORGANIC ACIDS

Fig. 1 - Schematic Diagram of Trickling Filter Process [by Permission of "Water and Sewage Works" (3917, p. 100)]

SECTION V

DEFINITIONS

During the evolution of the biological trickling filter on an international scale, the process became known under many names. Terms such as biofilter, percolating filter, sprinkling filter, sparkling filter, contact filter all refer to the process generally known as the biological trickling filter. Throughout the text of this report, these terms will be used interchangeably, but with the same meaning.

Based on studies by the American Society of Civil Engineers, the National Research Council publications (3053, 4916, 5590) and the Great Lakes-Upper Mississippi River Board of State Sanitary Engineers (5011), terminology has been evolved and recommended. The U. S. Federation of Sewage and Industrial Wastes Associations (5588) proposed the standardization of units of expression for design and operation of waste treatment plants.

> The biochemical oxygen demand (BOD_5) is a five-day test which has been used for several decades to evaluate the strength of the waste and the treatment plant efficiency (352, 1400).
>
> Depth of the filter medium is the distance in feet above the underdrains. The minimum distance is five feet and should not exceed seven feet.
>
> The distributor of the trickling filter may be the mechanical (rotary or traveling) type used commonly today, or the fixed nozzle type as used in years past, most of which were patented (224, 2830, 5574).
>
> Dosing has been used to describe the cycle time base that the waste stream is applied to the filter.
>
> The ecology (1826) of the trickling filter relates to viral particles as well as bacteria, fungi, algae, protozoa and invertebrates.
>
> Efficiency is the percent reduction of BOD of the primary settling tank effluent by a single stage trickling filter and the subsequent settling tank; i.e., $\frac{100 \times (\text{Influent} - \text{Effluent})}{\text{Influent}}$.
>
> Media or medium refers to the supporting structure on which microbial film develops such as rock, tile, wood, plastic, etc.

Preceding page blank

Nitrification is a phenomenon in which microorganisms (Nitrobacter, Nitromonas) oxidize ammonia nitrogen to nitrite and later to nitrate. In the early history of trickling filters the degree of nitrification was used to measure the efficiency of the process (658). With the development of the BOD test, nitrification was used only as substantiating information and in some cases, if nitrification has begun, creates confusion (360).

Pooling, ponding, clogging are terms used to describe blocking of sections of the media with biological or other material, causing the filter to short circuit, impairing the filter efficiency, and creating nuisance conditions.

Post-treatment is the several unit processes after the trickling filter treatment. The generated and sloughed bio-mass and the treated liquid waste are separated to improve the quality of the effluent stream to be acceptable to the receiving body of water.

Pretreatment refers to several processes preceding the trickling filter. The principal function is to materially reduce the load of suspended solids applied to the filter, reduce odors, or other waste conditioning prior to filtration.

Recirculation by pumping may be applied to the filter effluent, the clarifier effuent, the clarifier sludge, and mixtures of effluent. Several recirculation configurations have been developed, some of which are patented (274, 5574).

Recirculation ratio, R, is the ratio of the volume of flow recirculated to the volume of the average raw sewage.

Sloughing is the action of the biofilm releasing from the supporting medium and subsequently appearing in the effluent from the trickling filter.

Specific surface area (ft^2/ft^3) defines the actual surface area of the medium available for biofilm-waste stream mixing per unit volume occupied by the medium (2993).

Suspended solids of importance to trickling filters are those solid materials which are carried over from the primary clarifier and, after treatment through the filter, are discharged to the secondary clarifier.

Temperature of the waste as well as of the air is of concern in trickling filter design and operation.

Trickling filter loading has been expressed at various times as million gallons a day; population per acre or population per acre foot; pound of BOD applied per acre foot, pound BOD applied per cubic yard; pound BOD applied per 1,000 cubic feet; cubic foot per pound BOD applied, and pound BOD per square foot of surface (1029). To avoid confusion, there are two kinds of loadings when referred to trickling filters. One is the hydraulic loading, or the volume of the waste water, and the other is the organic loading, or the weight of oxygen-consuming material in the waste water. Confusion was also created in the units associated with these two loadings. Consequently, the U. S. Federation of Sewage and Industrial Wastes Association (5588) recommended: hydraulic load - gallons waste flow per square foot of media surface area per day (gal./ft^2/day); organic load - pounds BOD per 1,000 cubic foot per day of filter volume (lb BOD/1,000 ft^3/day) which was also endorsed by the Ten States Standards (5011).

Underdrains are substructures which support the filter medium and serve the dual function of carrying away the treated waste and sloughed material while acting also as ventilation ducts.

Ventilation of trickling filters is important to assure an aerobic environment and may be achieved by natural draft or forced air systems.

SECTION VI

HISTORICAL DEVELOPMENT

The history and development of the biological trickling filter may be undertaken with the assumption that an understanding exists of the purpose of sewage treatment (3851, 4317). Ancient and medieval waste disposal systems were comprised of collection, some sedimentation, and often land disposal filtration (1548). As populations become more concentrated, not enough land was available for filtration or sewage farms (589). Methods to artifically biologically treat waste were sought. According to Halvorson (1667), the first trickling filter, designed by Bailey Denton and built in Birmingham, England, in 1871, used soil as the filtering medium rather than rock. Expanded collection systems, such as that of London (2091), provided a challenge to the engineers to develop treatment works which would handle the large quantity of sewage. The application of chemistry and biology in the treatment of waste water was demonstrated by Rawlinson and others in England prior to the early 1900's (589, 602).

One of the early types of artificial treatment was the contact bed (698, 2984), which was a tank filled with a broken rock medium, intermittently submerged with sewage, allowed to soak, and then was drained to rest. The time required for this operation was usually on the order of two hours filling, contact for two hours, then draining and resting for six hours. In this manner, a four-foot deep bed, one-half acre in area, could handle 500,000 gallons/acre/day, allowing for resting and maintenance. This rate of treatment was too slow and required too much area, and the results of this operation were sometimes a nuisance to the community. Moreover, the reason for the contact or soaking period puzzled the engineers for many years (1667).

The method of distributing the waste to be treated over the medium has also been specifically reported (946). The first installations of trickling filters with distribution by spray nozzles were reported to be at Salford, England, by Joseph Corbett in 1893 (2984) and at the Lawrence Experiment Station in Massachusetts in 1891 (134, 690, 1667). The Lawrence Station has been credited with developing the use of the coarse grained medium (698, 1166). There was much competition for funds and manpower for the development of the biological treatment processes by systems which used chemical and/or mechanical means of treatment (130).

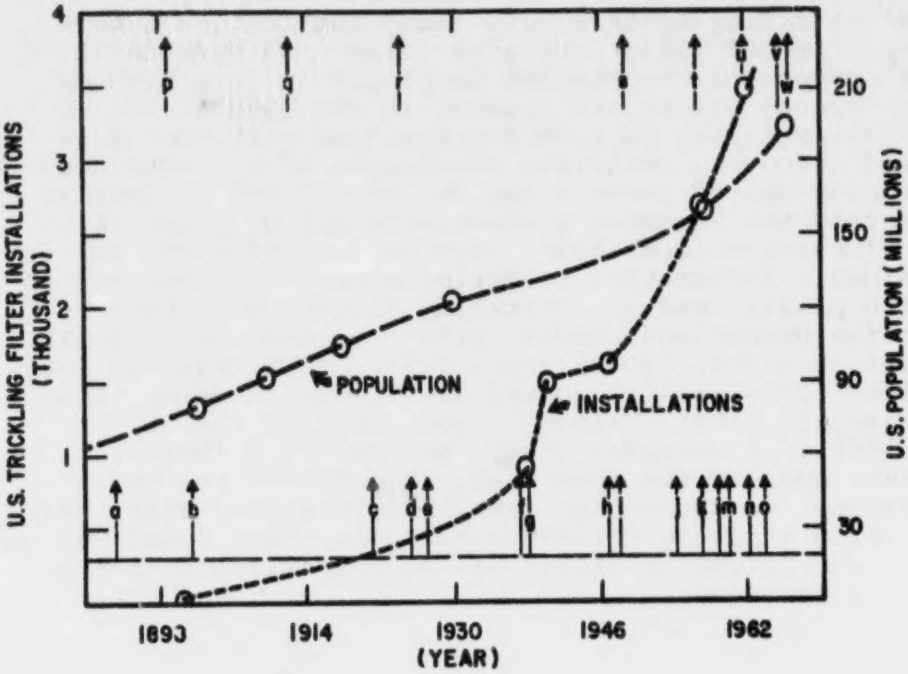
Development efforts were further promoted through the establishment of organizations such as England's Royal Commission on Sewage Disposal from 1898 to 1915 (589), the Lawrence Experiment Station (691) in this country, the Imperial Board of Health and Allied Scientific Institutions, 1908, in Germany (4723), and later the Water Pollution Research Laboratory in

Preceding page blank

England (5196), and the Robert A. Taft Sanitary Engineering Center in the United States. Chase (658) commented in 1945 on the 35 years of previous experience using trickling filters for waste treatment and the slow rate of development. It was noted by Stanley (4187), as by Chase, that the simplicity of operation of the trickling filter accounted for its popularity and also for the lack of development of the process. This period of arrested development was also noted by Imhoff (2210). The trickling filter (1166) was sufficiently popular that, in 1940, 58% of all plants in the United States providing secondary treatment utilized trickling filters. Though the percent declined by 1957, the number of trickling filter plants had increased to 2,682 and later to 3,506 in 1962 (85). The number of installations were indicative of the municipal waste treatment plants employing trickling filters. At most installations there were at least two and sometimes as many as 20 or 30 trickling filters. The trickling filter was common also at military installations and various institutions (5590). As noted in Figure 2, the rate of increase in the usage of trickling filters and in the population served has increased sporadically due to development influences, some of which have been noted by the various investigators.

Appurtenances for trickling filters were reported (2449) based on traditional uses and new intensive work which demonstrated the performance of the biological trickling filter under higher hydraulic loads (200 to 1,000 gal./ft^2/day). In 1937, Jenks (2306) developed the theory and design for biofiltration. The use of the concept of higher hydraulic and organic loading with recirculation by Montgomery (3074), 3077), Nelson and Lanouette (3161), Stanbridge (4168), and Fischer and Thompson (1280) resulted in a few patented processes. With the development of the high-rate biological trickling filters, design criteria were re-evaluated and formulations derived. The National Research Council (5590) in 1946 proposed a mathematical formulation, and in 1948 Velz (4535) reported equations relating the concentration of the waste to physical parameters involved in the biological filtration process to express the treatment efficiency. Mathematical description of the trickling filter process and its various modifications in the last decade and a half, e.g., Schulze in 1960 (3917) and Kehrberger and Busch in 1969 (2419), have occupied a considerable volume of literature.

The popularity of the trickling filter was increased by the development of the high-rate filters and also by the necessity of more accurate design work. Studies on retention time in filters (3981), the effect of recirculation (2419) and development of the alternating filtration system (1267, 3294) were among many of the problems attacked. Problems of controlling filter flies (738, 1407, 1960, 3886), the effect of medium (928, 1667, 2700), and other maintenance (1350, 4143) and operational (134, 1028, 2200, 5399) problems were also investigated at length.



Examples of Typical Influence Factors

a - Salford, England installation
b - Madison, Wisconsin installation
c - Rotating distributors used in U. S.
d - Activated sludge popularized
e - BOD test verified
f - High rate filter developments
g - Military application of high-rate
h - National Research Council report
i - Velz performance relationship
j - Plastic media used
k - Stack and Howland developments
l - Bloodgood influences
m - Schulze investigations
n - Behn evaluations
o - Galler and Gotaas studies
p - 1899-Rivers and Harbors Act (33 U.S.C. 407)
q - 1912-Public Health Service Act (P.L. 62-265)
r - 1924-Oil Pollution Act (P.L. 68-238)
s - 1948-Water Pollution Control Act (P.L. 80-845)
t - 1956-Federal Water Pollution Control Act (P.L. 84-660)
u - 1961-Amendments to the Federal Water Pollution Control Act (P.L. 87-88)
v - 1965-Water Quality Act (P.L. 89-234)
w - 1966-Clean Water Restoration Act (P.L. 89-753)

Fig. 2 - Factors Influencing the Use of Trickling Filters

Biological trickling filters have found application internationally. Imhoff (2210), Ehlgötz (1124) and Husmann (2136) used this process in Germany and developed it to a high degree (relative to the United States) in the 1930's. In England, Hurley (2110) in 1938 experimented with the basic process and cited the principal advantages of the activated-sludge process and of percolating filters (1199). Datesman (875) reported the advanced state-of-the-art of percolating filters. Investigations (5196) have been carried out to obtain valuable information to optimize this process, particularly with plastic media. Trickling filters have been operated in the Netherlands (2024, 2458), in Australia (1031), in New Zealand (3704, 3707), India (773, 4263), many in South Africa (1685, 2958, 4741), Poland (147), Russia (4254, 4840, 5448), Argentina (189), France (3955), Holland (2455), Uruguay (3842), El Salvador (630), and Malaysia (5087), to mention just some of the countries. Due to the low operating personnel requirements, developing nations, with their finances being strained for other purposes, have found many times that the trickling filter was an economic solution to their sewage problems.

SECTION VII

BACKGROUND THEORY OF PROCESS

This section briefly explores several topics dealing with the theoretical aspects of the biological trickling filter process. Theoretical and operational variables and their importance have been reported in the literature in a random manner. Where applicable, numerical limits or ranges of the variables are noted. Subsections are critiqued. This section should provide an insight into the thoughts of the investigators during the development of the theory of biological trickling filters.

An in-depth, well-documented theory of biological trickling filters has not been generally accepted (363), and continuing discussions of the inadequacies of the theories reflect the investigators' desires to develop a theory acceptable to all (2965, 3915). Reports are still being published dealing with various factors and their effect on the theory of biological trickling filters.

The development of the theory appears to have begun with rather general thoughts and observations. It was observed by workers, such as Herring (1898) in 1908, that contact surface area, suspended solids, air flow through the tower or bed, liquid contact time, temperature and distribution of the waste material over the filter affected the operation of the trickling filters.

With the need for construction of sewage treatment plants during World War II, design expressions for predicting the performance of biological trickling filters required adapting the theory into mathematical form. By observing the qualitative significance of each of the many variables, independent investigators developed several diverse opinions. Many texts summarize the existing theory of biological trickling filters, typically Metcalf and Eddy (2984), Pearse (3327), Babbitt and Baumann (112), Eckenfelder and O'Connor (1080), and Rich (3586), to list just a few. The information incorporated into these texts was basically derived from papers similar to those of Herring (1898), Husmann (2145), and Bachmann (134). Much of the early experience was reported in general terms and only occasionally were numerical values attached to trickling filter variables.

Quite often the theory was reported as introductory information (1075, 2663) on some specific aspect of the operational problems of waste treatment systems employing trickling filters. Reviews, e.g., Kleeck (2504) and Lohmeyer (2756), referred to the developed theory of trickling filters while pointing out operational factors in papers aimed at waste treatment plant personnel. Busch (549) in 1968 criticized the theory of the biological trickling filter and suggested viewing the system as a film flow reactor (similarly viewing the activated-sludge process as a fluidized system) under aerobic or anaerobic conditions, then using further theoretical refinements.

The separation of theory from the mathematical investigation is difficult after the efforts of a National Research Council (5590) and the development of their formulation. Investigators, such as Velz (4535), Fairall (1232), Stack (4157), Behn (246), Howland et al. (2065), Schulze (3917), Galler and Gotaas (1395), Germain (1460), Kornegay et al. (2547), Mehta et al. (2955), Robertson et al. (3647), Roesler et al. (3658), Kehrberger and Busch (2419), and Archer et al. (85) were very much interested in the proper applications of trickling filter theory, but the emphasis of their work was mathematical, as will be discussed later in corresponding sections. The significance in noting their work here is that, with the availability of the extensive data from the National Research Council's investigations (5590) plus the increased usage of trickling filters, these investigators were motivated to include their observations in the form of mathematical relations. In general, the same variables were being considered as those which were outlined in the early 1900's. However, the problem was now being critically investigated by determining the most significant of the variables.

To aid in the discussion of the theory of biological trickling filters, a schematic view of a trickling filter and the relationship of the many variables used in the theory relative to the filter structure are shown in Figure 3. That portion of the theory to be reviewed here was organized into the following categories: (a) the waste characteristics of organic strength and suspended solids, and their influences, (b) contact time, hydraulic dosing and load and their relationship on the filter behavior, (c) the filter medium, depth, surface area and effectiveness, (d) the underdrains and enclosures such as surrounding walls and roofs and this relation to ventilation, and their effect on performance, (e) the use of clarifiers and/or recirculation of the effluent and sludge, (f) ventilation and the oxygen content, and (g) interfacial factors relating to the biological film and the various transfer characteristics.

ORGANIC STRENGTH AND SUSPENDED SOLIDS

The influent quality of the waste being applied to the trickling filter as a function of organic and suspended solids content was recognized by Herring (1898) in 1908 in the term he described as "liquidity." Buswell et al. (555) were concerned with the removal of colloids from sewage and showed that this removal process was biochemical in

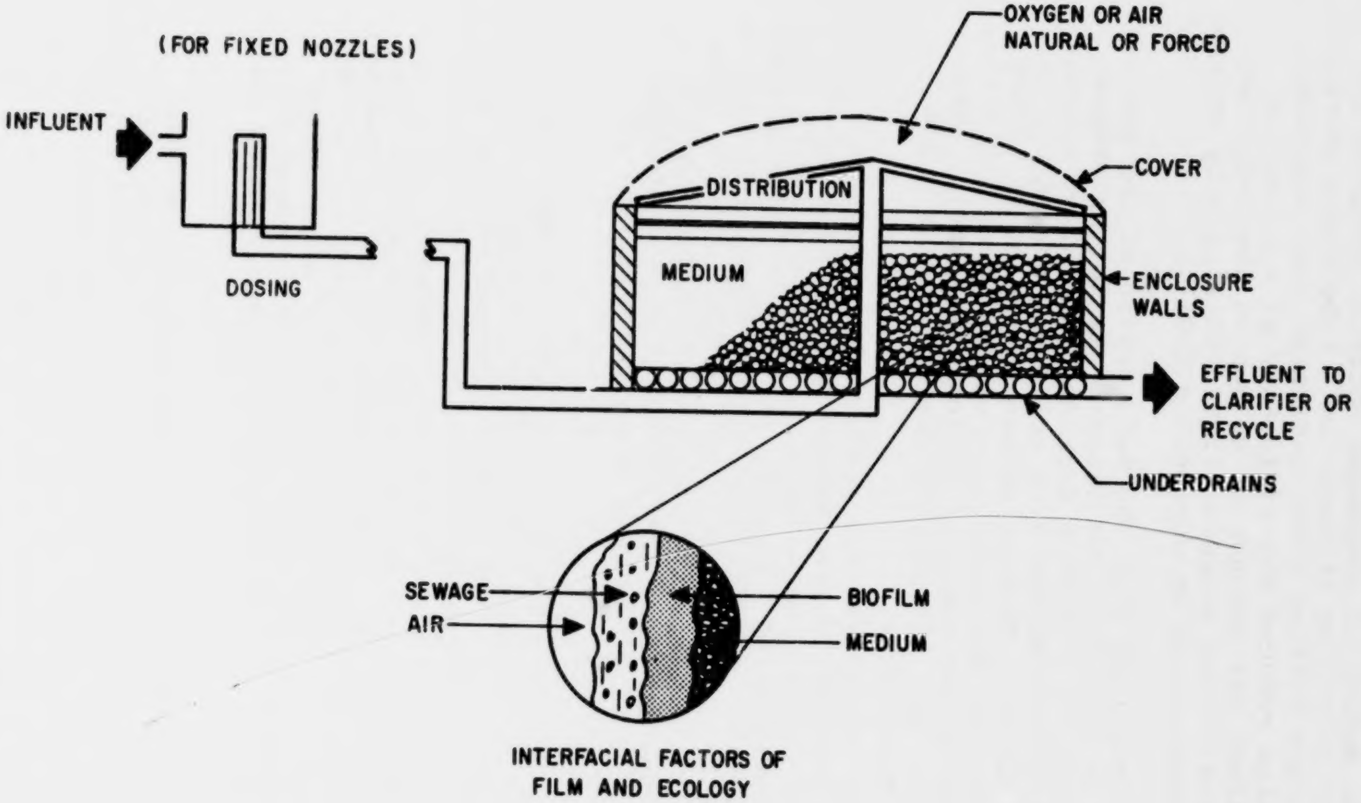

(FOR FIXED NOZZLES)
INFLUENT
DOSING
OXYGEN OR AIR NATURAL OR FORCED
COVER
DISTRIBUTION
MEDIUM
ENCLOSURE WALLS
EFFLUENT TO CLARIFIER OR RECYCLE
UNDERDRAINS
SEWAGE
AIR
BIOFILM
MEDIUM
INTERFACIAL FACTORS OF FILM AND ECOLOGY

Fig. 3 - Schematic of Theory

nature. Pönninger (3413), in developing calculations for sizing trickling filters, demonstrated that the strength of the waste and the amount of suspended material affected the efficiency of the trickling filter. In a laboratory investigation, Atkinson and Swilley (101) indicated that suspended and dissolved salts reduced the efficiency of a trickling filter. This effect was thought to be due to the reduction of the active area of the organism-liquid interface by entrapment of solid particles or by adsorption (101).

McLachlan (2928) reported that the main action of the process of purification by the trickling filters was not by combustion of the impurities to carbon dioxide, but rather a transference of the polluted matter from colloidal suspension to a coagulated condition. This point was supported by Levine (2704), who noted that the evaluation of the trickling filter efficiency solely on the basis of biological activity does not completely consider the physico-chemical coagulation properties of the process.

Pöpel (3428) also recognized the effect of the organic strength of the influent waste, determined as the biochemical oxygen demand (BOD). He found that organic strength is significant in determining the efficiency of the filter when he combined this with other factors into a simplified formula for evaluating the process. Velz (4535) reported that the efficiency of the trickling filter was proportional to the remaining concentration of the organic matter and this factor has been the basis of many later mathematical descriptions of efficiency.

While evaluating deep bed trickling filters, Burgess et al. (536) investigated varying organic strengths and hydraulic loadings on trickling filters. Data were obtained with an experimental filter on reduction of BOD and on nitrification which supported Velz's (4535) basic law. However, with the weak sewages examined, high hydraulic and organic loadings gave results much lower than those predicted by the theoretical formula. Meltzer (2964) concluded, during an investigation of contact time, that the increase in purification efficiency obtained with multiple stage filters, deep filters, and recirculation will be less with weak sewages than with strong sewages.

In developing a mathematical model, Kornegay and Andrews (2547) assumed that removal of organics is described by a saturation function which incorporates the effect of diffusion and growth rate. The effect of organic concentration and suspended solids is covered in this paper (2547). In analyzing trickling filter variables from a mathematical standpoint, Galler and Gotaas (1395) used organic loading as one of the major variables. They contended that the removal of BOD is affected most by the BOD in the influent as well as to a significant extent by recirculation, temperature, and depth.

Biczysko (322, 323) in 1965 indicated that, within a certain range of the load of organic matter, the efficiency of the biological process is independent of this load; when this load exceeds a certain critical value, anaerobic processes are responsible for the work of the filter. In developing a background for the use of plastic media, Pearson (3328) outlined factors affecting the design and operation of high-rate roughing filters, one of which is the organic content of the waste.

Critique

The involvement of suspended solids and organic content or strength of the sewage was recognized early in the development of the trickling filter theory. As the mathematical model was developed to consider the effect of these factors on the efficiency of trickling filters, divergent opinions were expressed. An example of the conflict of the theory is typified by the statement by Galler and Gotaas (1395), " . . it was found that the hydraulic rate did not contribute any significant effect to the BOD removal efficiency," in contrast to the statement by Schulze (3917)," . . . these results clearly demonstrated the hydraulic load and depth are two of the major factors determining the efficiency of trickling filters." Agreement and disagreement are reported with each of the views and the corresponding views on the influence of the strength of the sewage. Some light may be shed upon the matter if one relates the Galler and Gotaas approach to that of treating municipal waste primarily and that of Schulze to treating industrial waste principally. Galler and Gotaas made the comment that, "high hydraulic rates are indicative of high organic loading" (probably true for municipal waste), while Schulze made the remark that "organic load can be changed without any change in hydraulic load" (definitely true for industrial waste). It would appear then that the 322 field observations of Galler and Gotaas and the controlled model studies with field data applied by Schulze may actually support one another's conclusions.

CONTACT TIME, HYDRAULIC DOSING AND LOAD

An awareness of the significance of the retention time (contact time) of a waste in the biological trickling filter was shown by Herring (1898) in 1908. It was reported in England that 100 minutes of contact would give a good quality, nonputrescible effluent (1898). Blunk (367) and Pönninger (3406), using the salt concentration in the effluent tracer technique, determined that the contact time varied from one to five hours depending upon the type and size of material and the amount of film which had developed on the filter surface. Laboratory and pilot plant studies were used by Sheikh in 1966 (3981) to determine that the most suitable tracer was the radio-isotope Br^{82} in preference to the salt technique used above. Pönninger (3406) suggested the following retention hypothesis: each drop of water falling on a particle of the filtering medium spreads over the whole particle and penetrates the biofilm, mixing with the liquid already in the film; liquid is forced out of the film, collects in a drop on the underside and falls on the particle below. This explanation of the long detention times in the trickling filter was challenged by Stene (4207).

Contact time has been usually represented as the mean retention time as determined from a plot of the dye or salt tracer concentration in the effluent of the filter, as used by Blunk (367), Pönninger (3406) and Sinkoff et al. (4042). Sheikh noted (3981) that the mean retention time, as used by many workers (2064, 2963), was an inadequate parameter to define the retention characteristics of the filter, and suggested that it be replaced by the modal time and the standard deviation of the log normal distribution to compare and derive expressions for filter performance. Meltzer (2963) made an effort to relate retention time in filters with the rate of flow, the size of the medium, and the height of the filter. Howland (2064) proposed a theory, based on experimentation, which indicated that the degree of purification obtained depended upon the time of flow of sewage over the slime-holding surfaces on the porous media of a trickling filter. This theory implied that the time of travel through the filter varies inversely with the two-thirds power "rate of flow per unit width of plate." Escritt (1208), in preparing a paper on general considerations, stated that it was important to achieve a sufficient retention period for the organisms to effect oxidation. However, in contrast, Levine (2704) minimized the importance of oxidation. Escritt (1208) also reported that many investigators were of the opinion that an optimum condition was achieved "when the rate of filter loading was in the region of 900 and 1,000 gallons per day per superficial yard of the top of the bed" (100 gal./ft^2/day).

In laboratory-scale experiments, Bloodgood et al. (364) determined that the weight of biofilm on a trickling filter had no clear relationship to the waste contact time. Their studies demonstrated that the contact time on the laboratory devices was inversely proportional to the two-thirds power of the liquid application rate. Eckenfelder et al. (1083), while investigating retention times on plastic media, reported that the contact time is dependent upon hydraulic loading and distribution of the biological film. They concluded that the presence of the biological film considerably increased the mean residence time. Howland et al. (2065) investigated the capillary effect of water and the contact time on a laboratory simulation of trickling filters. Schulze (3915) proposed that the hydraulic load determined the period of contact and that this in turn determined the efficiency of treatment. He showed that the efficiency was inversely proportional to the 0.67 power of the flow, in agreement with Howland, Schulze, and Bloodgood et al. It was noted by Sheikh (3981) that the modal residence time was inversely proportional to the 0.7 power of the flow, which was in fair agreement with the values of 0.67 proposed by previously mentioned investigators.

Since the flow path of the waste through a trickling filter could be very tortuous, Meltzer (2964) proposed that a true Gaussian normal distribution curve would result when the lengths of the path were plotted against their number. The validity of this theory was experimentally verified and he further suggested that it is also an explanation of the difference of opinion held by many workers regarding the effect or organic strength and/or hydraulic load upon the efficiency of trickling filters. Mathematical expressions were derived by Sheikh (3981) for different sizes of medium, and the removal of organic matter was reported to occur in three stages along the depth of the trickling filter with up to 93% removed in about 30 minutes in the first foot of the filter. The liquid retention time for the same depth was 98.4 minutes, suggesting that a coarser medium in the first foot of the filter could be used. He also concluded that performance data obtained from pilot-scale filters can be applied to full-scale filters only if all the operating conditions of the two filters (depth, medium, and hydraulic surface loading) are identical. Of primary importance is the time of contact as reported by Biczysko (322, 323) in relationship to other variables, such as temperature, pH, type of medium, and amount of air supplied.

As noted historically, work has been reported on the frequency of dosing. Francis (1335) stated that by 1930 it was well established that the efficiency of the biological treatment depends on the closeness, frequency, and duration of the interfacial contact between the biologically active medium and the sewage with adequate available air. There was considerable debate dealing with intermittent versus continuous dosage, and Halvorson (1667) in 1936 indicated the trend was toward continuous dosage. Halvorson also supported the position of continuous dosing and indicated that rest periods are not justified for operation of properly designed trickling filters and that long rest periods are actually harmful to the performance of the unit. However, Levine (2704) investigated the various sizes of medium and dosing cycles which would produce more effective purification. With dosing cycles of 2.5 minutes, the rate of discharge was uniform and was approximately equal to the rate of application. A much greater reduction in BOD than normal was effected when the rate of outflow from the filter was uniform. Hydraulic distribution and its effect on the operation of high rate filters were studied by Kehr and Ruchhoft (2418), who found no significant difference in the efficiency due to rate, and by Jenks (2305), who stated that up to a recirculation ratio of six the reduction of BOD in lb/1000 ft^3/day of filter is practically proportional to the ratio.

Concepts such as minimum contact time and continuous dosage were recognized and employed by Jenks (2306), Halvorson (1667), and Levine (2704) as they developed and built high-rate biological trickling filters. Lanz (2629), in an effort to determine the highest allowable hydraulic loading rate, showed that 30.5 m^3/m^2/day of settled sewage per filter surface per day (32.6 mgad or 770 gal./ft^2/day) with sufficient aeration produced a nonputrescible effluent. However, the efficiency of the filter decreased with the increasing loads.

The term high-rate and high-capacity developed some controversy and confusion, as reported by Montgomery (3071). He specified that the total quantity of sewage through a filter in a day, or better still the total quantity of BOD handled per acre-foot per day was described by its "capacity" whereas the "rate" of operation is "the quantity of sewage it is capable of handling per second." However, the application rate per day (gal./ft^2/day) should be considered separately from the instantaneous hydraulic load, which could be a steady "rain-like" distribution or a heavy intermittent dose from the distribution box. Montgomery's comments had direct bearing on the type of distributor which was being used on the various high rate trickling filter installations, such as the "Aero-Filter" (Halvorson and Smith) and the "Bio-Filter" (Jenks), which were classified, respectively, as low rate with high capacity and high rate with low capacity. Covill (807) in 1942 used the high capacity designation in a discussion of trickling filter and other types of biological treatment. He concluded that high capacity filtration in its various forms offers distinct advantages in lower construction costs, reduction in odor control and fly nuisance, nonclogging of filter media, and production of an effluent (two-stage treatment) equal to that from an activated-sludge process.

In addition to hydraulic rates being increased, other modifications were described by Tomlinson (4422), such as two-stage operation of trickling filters with the order of their dosing being alternately reversed. This alternating double filtration system could treat 2.5 times as much sewage as a single filtration system with no particular effluent quality degradation as judged by the BOD test. In 1958 Nelson and Lanouette (3161) summarized the investigations leading up to the design of the Bio-Filter and described the basic principles of the other patented high-rate treatment methods such as the Ward, the Aero-Filter, and the Accelo-Filter methods. Formulae derived from the National Research Council in 1946 for interpreting results of filter performance were applied to single- and two-stage filter design and the relationships illustrated.

Later, Meltzer (2965) agreed with Montgomery (3071) that biological filter efficiency was considered to be a function of the "intensity of hydraulic surface loading rate." Maximum efficiency occurs at an optimum rate of flow which is specific to the type, size and configuration of the medium. There was no evidence that two-stage filtration or recirculation of the effluent would be any more efficient than single filtration with deep filters. However, Sorrels and Zeller (4111) reported on the advantageous use of two-stage trickling filters without intermediate sedimentation, giving a higher degree of purification than single-stage filtration, even at higher hydraulic load. The primary filters were heavily loaded hydraulically and organically without recirculation and were actually operated as roughing filters.

Critique

The use of the mean residence time to represent the contact time in the filter has been shown to be inferior to the use of the modal time. However, the contact times were very closely related to the inverse of the hydraulic load raised to the two-thirds power (2064, 3915, 3981). Comments (364) on the relationship of the biofilm to retention time appear initially to be in conflict. However, one investigator (1083) noted distribution of the biofilm, and the other (364) was measuring total film accumulation. The hydraulic considerations are noted here to demonstrate the awareness of the investigators. General practice has evolved from the use of intermittent discharge at high rates to continuous discharge at low rates. The latter hydraulic application rates were based upon a better understanding of the significance of the retention time or contact time in the filters. The concepts of high-capacity and high-rate very clearly identify the limitation of the early designed trickling filters. In the Design Section (Part II) on hydraulic loading, it will be noted that much higher hydraulic loadings were made possible by the use of fabricated media.

FILTER MEDIUM

The principle behind the use of a filter medium was to supply an inert supporting structure to which the biological growth can adhere. It has been reported (2816) that some slag media exhibit a sorptive property which was desirable for industrial waste treatment.

Herring (1898), Husmann (2145), and Kleeck (2504), with 50 years of combined experience, emphasized the importance of the available superficial or contact area of the medium. Pöpel (3428) and Meltzer (2965) identified the significance of surface area characteristics of the medium in their respective theories and formulations. A finer grained medium was reputed (1667) to have greater surface area, but also would clog more easily. Recognizing that a deeper, more porous medium was important, investigators, such as Halvorson (1667) in 1936, used fabricated media such as tile. Pearson (3328), almost thirty years later, used plastic media which were designed for greater bed depth, greater surface area, greater void space, and other desirable operational factors. Comparisons of media have been made in several studies (1083, 2992, 4463).

Strickhouser et al. (4252) and Walton (4596) have demonstrated the importance of the depth of the medium. They stated (4252) that, theoretically, a greater depth of the filter resulted in greater rate of purification. However, practical considerations of the medium, due to trouble with ventilation and sloughing, limited the depth of the filters. Walton (4596) claimed, in 1950, that the quality of the filter effluent is dependent upon the depth of the filter medium rather than its volume. Biczysko (323) and others (536) reported that the bed height or depth was significant in determining the efficiency of the trickling filter. Velz's formula (4535) included a parameter for the depth of the filter.

Critique

Practically, the design criteria required of a medium for a trickling filter operation are covered in Part II. The workers listed above were aware that the medium should be fairly inert to biological and chemical interactions of the sewage effluent with only minor changes over a long period of time. The medium should have adequate space for ventilation and sloughing of solids. The function of the depth was not clearly understood for some time, but it should be noted that recirculation and two-stage applications were used so that, in effect, deep beds were in operation for a long time. Later, oxidation towers tens of feet high have been used with and without recirculation. The conservative nature of the engineers and scientists protecting the public forced them to rely on media which had been proven over the years. Media other than rock, such as tile and plastics, are being used at an increasing rate as the result of extensive efforts of media fabricators. With better understanding of the desirable medium properties, additional materials and designs will undoubtedly be used.

UNDERDRAINS AND ENVIRONMENTAL CONTROL

The underdrain systems, enclosures of wall and roof, the temperature control, and nuisance control are all very closely related. The necessity of providing properly sized underdrains to carry the flow and supply necessary air to the filter was known by Corbett (787) and Halvorson (1667) and was well established in the early 1900's (1898). The Trickling Filter Floor Institute (5574), in their technical information bulletins, published the results of several investigators along with detailed descriptions and illustrations of underdrain systems. Much of this work is based upon acceptable practice and is therefore reviewed accordingly.

By putting walls on the trickling filter the fly larvae could be drowned by flooding (1667). Lohmeyer (2756), in a review of the operation of trickling filters, discussed the type and sizing of the underdrain system and the use of walls enclosing the trickling filter. Complete enclosure of the filter, such as was reported by Husmann (2145) as a means of controlling odors and fly nuisances, was not uncommon.

The influence of temperature, as investigated by Lanz (2629), indicated results which could not be generally agreed upon, e.g., the temperature of the sewage remains practically unchanged during the purification process and no noticeable cooling occurs in the winter. However, Petru (3342), in discussing the work of many investigators, observed that some cooling occurred in the effluent from the filters and this cooling was affected mostly by the individual filter medium characteristics. Howland (2063) proposed a mathematical relationship which considered the effect of temperature on the biological filter efficiency. The temperature effects were investigated by Schroepfer et al. (3903); however, the effect of temperature on the operation of a filter was acknowledged by Biczysko (323) as being only secondary.

Critique

Brief mention of temperature, nuisance, underdrains, and enclosures was made to demonstrate the awareness and concern of the investigators. Information dealing with the specific application of these aspects to problems is provided in Part II of this report. The effect of temperature is, at best, not fully developed but sufficient work has been done to include it. Walls surrounding trickling filters are in common use, and problems dealing with ventilation blockage were solved. However, with the advent of high rate trickling filters and fabricated media, the necessity for flooding was not as great. Therefore, structural walls have become less important. Nuisance control dealing with odor, flies, and ice formation has been handled quite well in specific localities by chemical and/or enclosure techniques. Enclosure of trickling filters for nuisance control is being continued due to increased public attention.

SECONDARY CLARIFICATION AND RECIRCULATION

The theory behind secondary clarification after the trickling filter and recirculation has progressed through several stages of development. Clarifiers as part of the trickling filter process were routine prior to 1900 (1898, 2504, 2925). Since the biological trickling filter mechanism was thought to be adsorption of colloidal material and complexing soluble organics into settleable solids, there were only a few installations built without secondary clarifiers. Kleeck (2381) presented a review of the performance of clarifiers. Sorrels and Zeller (4111) and others (85, 5574) were interested in operating two-stage filtration plants without intermediate clarification. It was reported (85) that in the operation of a two-stage system the intermediate clarifier had no effect on overall efficiency. In most instances, it was found highly desirable to follow the second trickling filter operation with a clarifier (853, 4630). Fischer (1286) supplied data that were useful in design evaluation of clarifiers and filters.

Recirculation of trickling filter effluent was utilized prior to 1940 (3406, 4207). Newly developed accelerated methods of biological treatment took advantage of recirculation (2544). Meltzer (2963, 2964, 2965) described work covering ten years which was indicative of the continued interest expressed by several investigators in the use and effectiveness of recirculation. His studies led him to believe that an increase in treatment efficiency due to recirculation actually does not exist when the total system is considered. However, Benzie (274) stated that very good effluents from high-rate filtering plants have been obtained at recirculation ratios of from 0.5 to 1. In the development of the trickling filter theory, the National Research Council (5590), Galler and Gotaas (1395), and others (2064) included recirculation in addition to other variables.

According to Galler and Gotaas, recirculation of effluent can improve the quality of the final effluent discharged to a certain extent, but with more than four volumes of recirculated liquid to one of plant influent there is no improvement. Dreier (1029) strongly recommended the use of recirculation based on system evaluations. The only effect recirculation had, as claimed by Germain (1460), was that one was able to maintain a constant rate of dosing. Studies at Mississippi State University (85) using the National Research Council formula indicated that recirculation improved overall efficiency of the plant. Leibee et al. (2670) found that for best filter efficiency a minimum as well as a maximum loading must be considered, i.e., controlled recirculation. Very recently, Kehrberger and Busch (2419), using mathematical models to describe the effect of recirculation, reported the results of a mathematical analysis and laboratory experiments of the effect of recirculation on removal of total soluble organic carbon. Two of their conclusions were: " . . . (A) For heterogeneous film flow reactors, recirculation has a detrimental effect on removal of total soluble carbon; and (B) for pseudo-homogeneous film flow reactors, recirculation has a beneficial effect on removal of total soluble organic carbon . . ." Pseudo-homogeneous film flow is defined as a film flow system in which liquid entering the reactor flows through or contains the microbial mass and reacts at all points in the liquid phase. Data are given for a glucose system from which they draw the cited conclusions. Roesler et al. (3658) prepared a mathematical model for recirculation, in which the cost of recycling was also included.

Critique

The use of clarifiers in various stages of the process has been adequately investigated. As a design consideration, intermediate clarifiers may or may not be economically used. The solids balance of the process and waste are prime factors. Theory is well established for the solids-liquid separation. Design standards have been reasonably established (5011, 5331).

The advantage of recirculation, however, has not been well established from a theoretical basis and the search for a solution of the problem has gone from laboratory study to field empiricism and back to laboratory study. It would appear that Kehrberger's work (2419) lends definite support to the diverse mathematical and experimental effect of recirculation. By the definition of his film flow model, his conclusions imply that recycle of clarified effluent degrades the treatment plant efficiency, whereas the recycling of sludge and some effluent improves the efficiency of the trickling filter process. This is of interest, if correctly interpreted, because recycling of sludge into the active biological reaction system, such as the trickling filter, would cause more harm than good due to the complexed organics in the settleable solids being released in a soluble form and possibly escaping via degradation. It has also been reported that recycling of effluent dilutes the waste, thereby dropping efficiency. It will be most interesting when Kehrberger's conclusions are put into practice with current process technology and evaluated under field conditions.

VENTILATION OF FILTER

Early in the 1900's and before, Nasmith (3147), Corbett (787) (1667), and others (1626) explained the principles of aerobic treatment and the necessity for adequate availability of oxygen in the biological trickling filters. Levine (2698) studied the effect of bottom ventilation on the trickling filters and found that while the mechanism was not explained there was a definite detrimental effect when ventilation was blocked. Tatham (4296) stated that a measure of pollution in a waste liquor is dependent upon the oxygen required for its complete oxidation and that the rate of absorption of the dissolved oxygen is proportional to the concentration of the polluting material. He then suggested an "avidity" constant, a numerical measure of the activity of the biological oxidation, which is dependent upon the type of waste being treated and the circumstances under which oxidation is taking place.

Measurements of the content of carbon dioxide in the gas phase were made (2629) and it was demonstrated that the dissolved oxygen content of the sewage increased slowly as the waste passed through the filter. However, a tour of a number of European waste treatment plants by Rudolphs (3741) prompted the observation that the results of the operations of some sewage treatment plants did not support the theory that the biological activities in the trickling filters are limited by the oxygen content and that the carbon dioxide concentration in the lower parts of the filter is toxic to the oxidizing bacteria. McLachlan (2928) added further support to these observations by discrediting the effect of carbon dioxide in the biological trickling filter process. However, concern was still expressed by Husmann (2145) that not enough oxygen was available in normal ventilation of trickling filters to maintain the activity of the aerobic bacteria. Since the upper part of the trickling filter exerted the most biological activity, he suggested that the efficiency of the filters could be possibly raised by increasing the available oxygen by artificial aeration.

Halvorson (1667) reported that forced aeration is essential during seasons when the air and the water temperature are approximately equal and the ventilation of the trickling filters is at a very slow rate. Petru (3342) took exception to this view on aeration in trickling filters and suggested that the most favorable conditions for movement of air occur near the surface, which places shallow filters at an advantage over deep filters.

Heilmann (1860) described investigations and development of artificial aeration or ventilation for trickling filters as a method of controlling nuisances and securing better operation. The case of limited space and a required degree of treatment was outlined by Kominek (2544), in which he suggested artificial aeration as a method of accelerated waste treatment with the possibility of using oxygen instead of air. Sufficient surface area of liquid exposed to the air plus sufficient turbulence of the liquid to produce the degree of aeration needed were factors described by Escritt (1208) as being necessary to effect oxidation of organic material.

One of the factors that Biczysko (323) cited as being of some significance was the air supplied to the Bio-Filter. Pearson (3328) stated that air velocities of 6 ft/min are more than adequate to supply the oxygen requirement of filters with 50% void space. Eckenfelder et al. (1083), in studying the performance of fabricated media, reported oxygen transfer capacities of 0.0162 lb/hr/ft at a hydraulic load of 3 gal./min/ft^2 (4320 gal./ft^2/day). Confidence in the ventilation properties of existing technique was expressed (5574) and documented with full-scale operational data. The deeper bed installations have been shown to generate sufficient draft for ventilation (4330, 5637). Problems with high organic wastes from acid fermentation of molasses have been reported by Krige (2571), in which normal aeration of the molasses slop in admixture with sewage before filtration was not satisfactory.

Critique

Perusal of the literature dramatizes the conflicting evidence in the effect of ventilation on the efficiency of trickling filters. However, it is common practice today to build deep bed filters operating under natural draft conditions. Exceptions arise; if an extremely high oxygen consuming organic waste is being treated and the filter is acting as a roughing tower, then forced ventilation may be used. Even the use of enclosed filters does not necessarily mean that forced ventilation is necessary. It is recommended that the underdrain system must be designed and operated to flow only partially full, allowing free access for air movement above the liquid level. Internal and external temperature differences will usually generate sufficient air movement to supply adequate oxygen under normal conditions. Additional information on ventilation is reviewed in Part II, "Design and Construction."

INTERFACIAL BIOFILM INVESTIGATIONS

Knowledge of the reactions occurring on the surface of the medium, the biological film and the waste stream at what one might call the interface (refer to Figure 3), was clearly demonstrated prior to 1911. Nasmith in 1911 (3147) described the reactions which were taking place in the trickling filter as chemical, thus organic matter plus oxygen give inorganic matter and humus. In a discussion of Francis' work (1335), Harris pointed out that the important difference which exists in trickling filters versus other biological processes is that each stratum of a percolating filter continuously performs the same biological functions. Rudolfs and Gehm (3755), discussing colloids in sewage and sewage treatment, suggested that aerobic biological treatments, e.g. treatment by the activated-sludge process and in trickling filters, depend on surface activity of the gels of biological origin which are formed. The action may be due to surface attraction, formation of adsorption compounds, or concentration of food materials for bacterial growth. Adsorption of soluble matter may be due to base exchange, and a theory of adsorption of dispersed matter by neutralization of electric charges was advanced. This adsorption theory was used to account for the rapid removal of soluble matter and was supported by bacteriologically identifying the microorganisms (555). Similar to this work, about 40 years later, cultures of Zoogloea were shown (1775) to coalesce with small flocs, suggesting a mechanism of colloidal entrapment by this life form.

Blunk suggested (367) that biological treatment in the trickling filters occurred by liquid displacement in the film layer, similar to the hypothesis postulated by Pönninger (3406), and that the Paramecia activity of the biological film was an indication of the biological activity available. Colloidal, biological, and enzymatic theories were discussed by Theriault (4353) to explain the phenomenon which he called "clarification." This "clarification" was used to denote the overall improvement which results from treatment of sewage for a brief period, but does not provide complete removal of turbidity in the 30- to 40-minute time limit.

Several investigators (364, 1208, 2064) demonstrated an appreciation of the surface flow regime and the biological film-waste interface as they function in the overall removal of organic waste. The influence of turbulence on bacterial slimes was discussed by Hartmann (1775) who showed that turbulence is important in the transport of food molecules from the environment to the surface of bacterial cells. An attempt was made by Swilley et al. (4277) to use transport equations to describe simplified biological oxidation systems.

In the development of the feasibility of using synthetic plastic materials as a filter medium, Pearson (3328) indicated six basic steps as a biochemical basis of biological flocculation which included: (a) adsorption of dissolved and colloidal organic matter to the outside biofilm; (b) breakdown of large molecules by extracellular enzymes and absorption of small molecules into cells; (c) growth of the primary population, food storage and cell division; (d) ingestion of primary flora by secondary grazers; (e) endogenous respiration of carbonaceous matter by all members of the bios with release of ammonia to biofilm; and (f) oxidation of ammonia to nitrite and nitrate by autotrophic bacteria. Biczysko (322) indicated activity of the biofilm as a parameter of primary importance. Wintz (4776) referred to his thesis in which he showed that the microbial content of the biofilm averaged 550 million bacteria per gram of film, 80% of these being gram-negative rods and 12% being gram-positive spheres, and the predominant bacteria changing with every test.

In 1966, Sanders (3823), reporting on the oxygen utilization of slime organisms in the stream environment, concluded that under the experimental conditions and in a steady state condition the oxygen utilization of the total system will remain constant with respect to time. Although the thickness of the slime mass of the attached organisms increases linearly with respect to time during this steady state phase, the rate of oxygen utilization remained constant. The averaged thickness of the slime was 11 μ (0.011 cm) while the minimum thickness for diffusion of oxygen was 21.2 μ (0.0212 cm). Maier (2837) showed that increasing the thickness of the slime beyond 48 μ (0.048 cm) had no significant effect on the organic removal under the laboratory conditions studied and that the mass transfer is the rate limiting step except at high feed concentrations. Sanders (3824) previously reported that the growth rate of slime bacteria under stream conditions was limited when the attaching surface became completely covered with one layer of cells. The maximum rate of nutrient removal from the substrate occurred when the slime thickness equaled the limiting thickness for the diffusion of oxygen.

A mathematical model, called the "cell model," to represent the trickling filter used for biological treatment of organic waste was proposed by Busch and Hughmark (548). This model assumes that the substrate and oxygen are consumed at the surface of the inclined plate and that the liquid film can be divided into a number of rectangular cells. The model considered the consumption of glucose at the biological surface on the plate and diffusion of glucose and oxygen through the liquid film to the biological surface. Comparison of the data calculated from the model with experimental data for an inclined plate indicated that the liquid film flow was not laminar. Good agreement was obtained between calculated and experimental glucose concentrations. The following year, Kehrberger and Busch (2419) developed a mathematical model based on three theoretical film flow models which deal with various concentrations of organisms in the liquid film which are present in a recirculating trickling filter process. Kornegay and Andrews (2547) developed a mathematical model for a fixed film reactor which describes the rate of substrate removal from zero-order at high concentrations to first-order at low concentrations, which are not usually covered by current design equations used for deep trickling filters. The biofilm reached a constant thickness of approximately 200 μ (0.20 cm) at which point the shear on the film surface was sufficient to wash the newly formed organisms into the liquid phase.

Critique

The intent of reviewing the various theories proposed here was to indicate, briefly, the thinking which has gone into the development of the theory of biological trickling filters. To start with general observations, then develop empirical relationships, to be followed later by rational design and the theoretical models has been the historical development for the biological trickling filter process. As shown in the exploded view of the surface of the trickling filter in Figure 3, there are many reactions taking place simultaneously under varying conditions. In the sewage plant, these reactions generate an extremely complex problem which still confronts engineers and scientists of today. A grave drawback is the lack of applicability of the usual high level kinetic-mathematically oriented papers.

It is very unfortunate that more authors have not followed the examples of investigators such as Busch to attempt to relate mathematical theory to the solution of real problems. Quite often workers, especially in the investigation of the biofilm, in disciplines other than sanitary engineering, have not made the attempt to relate their work so that the practicing engineer can appreciate it. The result is that the contributions of the scientists are regarded as "blue-sky" and irrelevant.

PART II

PLANT DESIGN, MATERIALS OF CONSTRUCTION, OPERATION MAINTENANCE, AND PERFORMANCE

This section details the literature of the trickling filter in five broad categories. The first category concerns design, illustrating the criteria which have been used during the development of trends in providing secondary treatment with biological trickling filters. The second section describes the materials of construction for the various components of trickling filters. The third deals with various operational techniques which have been employed for biological trickling filters. The fourth consists of maintenance techniques and problems resulting from the operation of trickling filters. The fifth category is composed of a performance summary of the biological trickling filters and the formulae developed for process evaluation.

SECTION VIII

DESIGN CRITERIA OF VARIOUS TRICKLING FILTER MODIFICATIONS

The current design criteria have been the result of an international effort. Investigators in England, Germany, France, Russia, South Africa, South America, the United States, and many other countries, have been working to develop these criteria (189, 371, 1190, 1690, 3955, 4840, 5378). The design criteria have been organized and categorized according to the type of waste and plant, hydraulic and organic load aspects, combined use of the trickling filter with other secondary processes, and economic considerations. This organization was made because the primary differences in the modifications of the trickling filter are concerned with hydraulic or biological load. Other factors such as the media used in the filters, the ventilation requirements, pretreatment, post-treatment, and solids disposal are, to a degree, similar in each of the modifications and are treated accordingly.

A basic appreciation of the design problems may be drawn from many textbooks (112, 308, 1080, 2984). Escritt (1195) observed that the Fifth Report of the Royal Commission on Sewage Disposal issued in 1908 has had a great influence in developing the designs involving percolating or trickling filters. Especially in England (and later in this country), the recommendations of the Royal Commission were interpreted with almost the same acceptance as a statute of the land. A classic example was cited by Escritt, "But at the present time by far the greater number of percolating filters are being constructed to an exact depth of six feet," with very little justification other than it had been used in the past, worked fairly well, and was recommended in the Royal Commission report. In the design of sewage treatment plants, arbitrary depths, loadings, retention times, etc., are sometimes used, but the usage of arbitrary parameters is less prevalent.

Buswell et al. (555) in 1928 and Bloodgood (363) in 1956 reported that considerable progress had been made in the development of biological trickling filters, but that it was apparent that not all of the information published on the theory and design was in agreement. Spurts of activity in developing design criteria have been reported (1326, 4640) but, unfortunately, as others (658) have noted, new developments in design are slowly accepted. However, with more operational experience and the data released by the National Research Council (5590), a basis for rational design was developed after World War II (3076) and specific problems were identified and attacked on the new processes, such as the high-capacity trickling filters. Greeley (1564) outlined considerations in the design of high rate trickling filters as influent, effluent, waste characteristic, effect of recirculation, localized factors such as temperature and degree of treatment required, and overall cost and economy of the process. Mathematical interpretations of

Preceding page blank

the above factors were given more consideration after the publication of the critical study of the design and operation of several hundred military treatment plants by the National Research Council (5590). This study provided design information useful for treating sewage uncontaminated by industrial waste waters. Baker and Graves (150) in 1968 reviewed several design formulations and concluded that more accurate data are required to establish the validity of the different formulas and to determine the effect of filter efficiency parameters on volume requirements.

There are many divergent viewpoints, e.g., those of National Research Council (5590), Eckenfelder (1081), Galler and Gotaas (1395), Schulze (3916), Velz (4535) and Howland (2064), since there are many varied applications of the trickling filter and its modifications which have been developed over many years in different geographical areas.

TYPE OF WASTE

In the review of design, the influent waste characteristics are of primary importance. Generally speaking, there are essentially two types of waste streams, municipal waste and industrial waste. Practically speaking, it is only rarely that one of these two types of waste is treated solely by itself. Mixed waste normally exists in practice, but frequently the mixed waste stream can be treated as either municipal or industrial waste, depending on the relative proportions in the waste. For example, a waste stream containing a high phenolic content with some domestic sewage from a chemical processing plant would be termed an industrial waste, whereas a waste stream entering a major metropolitan waste treatment plant with minor industrial contribution would be regarded as municipal waste, with a contributory industrial waste influent.

Combined sewers (sanitary and storm) further complicate the problem of wastewater treatment and consequently the functional design of biological trickling filters. Approximately 28% of the population of the United States which are served by sewers have combined sewer systems (3954). These systems deliver an influent to the waste treatment plant which has extreme variations in flow and organic loadings. The storm water causing these variations has been a problem overseas (2879, 5549) and in this country, as summarized by the Federal Water Pollution Control Administration (3631). The very frequent use of the trickling filter to handle municipal waste may well be based on the fluctuating flow experienced at most small treatment plants (2687, 2970, 3053).

In many municipal plants, the situation where supernatant liquid from the anaerobic digester is pumped back through the filters is further complicated (3076). The design must take this additional load in consideration. Typical of the problems generated by this recycling supernatant technique is the development of odor problems (4187) which must be minimized by appropriate design. There are literally hundreds of articles, as noted in this review and will be discussed later, in which the biological trickling filter is used in municipal waste treatment plants. Industrial wastes have been treated extensively (307, 546, 2977, 3312) by biological filtration. The importance of biological trickling filters to handle industrial waste was reflected in the literature to such a degree that Part IV of this review is specifically concerned with the application of the biological trickling filter to industrial wastes.

A prime advantage of the trickling filter in industrial waste treatment applications is the ability of the filter biota to survive shock loads of toxic waste, elevated temperature, high oxygen demand, and other rapid changes which may occur in an industrial waste disposal system. It has been noted by Busch (546), Eckenfelder (1078) and McKinney (2925) that it is not because the microorganisms are any more hardy in a biological trickling filter than in any other biological system, but that survival is actually due to the relatively short retention time in the filter (546) and that contacted and killed organisms are flushed from the filter, exposing another layer of microorganisms not subjected to the shock load (1078).

Critique

The trickling filter emerges as a versatile treatment device with many advantages. The filter is so constructed that it is highly resistant to hydraulic overloading and to shock loads of organic or toxic material. The demands on the operator for skilled management are nominal or absent so that the trickling filter works effectively in the hands of unskilled people. The filter is accordingly favored for small installations.

Since filters may be made with considerable depth and because they cope effectively with a wide range of difficult waste problems, the role of the filter is by no means limited to small installations. It continues to be an effective device, requiring consideration whenever biological treatment of wastes is contemplated.

HYDRAULIC AND ORGANIC LOADING

In this section, hydraulic and organic loading for the trickling filter and its modifications are discussed. A very brief description of many of the modifications is provided along with the design considerations.

Contact Beds

The contact tank was a step between land irrigation as a waste disposal procedure and higher rate systems such as the trickling filter and the activated-sludge process (2159). Several texts have been published (348, 1040, 1727) which generally related the advantages, disadvantages and general design criteria of contact beds. Prince Albert of England (4463) in 1850 proposed the use of a system employing charcoal, gypsum and burnt clay laid up on a false bottom and subjected to an upflow of sewage to provide purified water and a source of fertilizer.

Clark (698) reported on the extensive studies which began in 1894 at the Lawrence Experiment Station. The various factors affecting contact beds were discussed, such as efficiency of different materials, double-contact filtration, i.e., recycle or two-stage, disposal of nitrogen, permanency of contact beds, composition of organic matter, best methods of operation, rate of flow and different depths. Adequate information was provided in the 1930's by Metcalf and Eddy (2984) in the third edition of their book on sewage. A description of the contact bed based on their information was as follows: A rock medium, 1/3" to 3" in diameter, is piled to a specified depth (4 to 6 ft in this country and 2.5 ft in England) and primary influent is applied. The dosing sequence consisted of filling for two hours, contact for two hours, then draining with 6 hours' rest. For a 4-ft bed covering 0.5 acre area, 0.5 mgad (11.5 gal./ft^2/day), allowing for resting and maintenance, could be treated. The operation was flexible, depending on the number of fillings per day. However, contact time greater than two hours gave inferior results. Distribution of the sewage was by filling lateral underdrains and pipes, and troughs similar to underdrains common in trickling filters. Maturing or conditioning time of the bed (for anaerobic film build-up) required from a few weeks to several months. When the medium became clogged, the solution was removed and the media washed. The contact bed had fewer odors and flies than the trickling filter. Preaeration usually guaranteed nitrate formation in the effluent. Single, double, and triple stages were used (2984).

The literature (1064) reflected successful use of contact beds for municipal and industrial waste treatment. However, in the first decade of 1900, sprinkling filters were preferred to contact beds because of the greater capacity of the filters (3220, 5059). Contact beds were relegated to the solution of waste treatment problems for remote locations (486, 3982), such as institutions, recreational sites, military installations (2620), and other low population areas. With increasing popularity of trickling filters, methods to convert contact beds into storm water tanks, sludge drying beds or trickling filters were developed (159, 3441, 3951).

The obsolescence of contact beds is attributed to the higher efficiency of trickling filters. The contact bed is of historical importance only.

Dipping Contact

A slightly different variation on the contact bed principle was given by Allen (38) and Doman (990) in the late 1920's and early 1930's. Allen (38) reviewed Buswell's work (556) on a series of paddle wheels supported over a channel of waste. The wheels were rotated by the flow of sewage, the blades thereby being alternately submerged and exposed to the air or in "dipping contact" with the waste. Doman (990) described difficulties of anaerobic film build-up on an experimental contact filter with partially submerged rotating plates. Schmitt (3879) discussed Kessener's system (2452) in which revolving brushes placed along one side of the tank dip into the liquid to a distance which can be varied according to the aeration required, and concluded that it was a feasible waste treatment device. It is probable that this system was a forerunner to the brush aerators.

The approach of moving the medium alternately through the waste stream and the atmosphere was recommended much later by Reid et al. in 1960 for the treatment of high phenolic-type waste (3547). Concentrations of up to 7500 mg/l phenol have been treated by this method. Hartmann published a series of papers (1769, 1770, 1771, 1772, 1773) on the advantages and operation of the dipping contact filter and its application to several types of industrial wastes. The advantages of this process are adaptability to varying loads, concentrations and degrees of treatment, low cost of construction, ease of operation, and a greater resistance than the activated-sludge process to dilute poisons, mineral oils and detergents (1769). He has applied the method to the treatment of sewage, and mixtures of sewage and trade wastes, including those from dairies, breweries, maltings and canneries (1773). This technique (1771) used rotating disks which were made from expanded polystyrene strengthened with unexpanded plastic and separated by metal spacer disks. The plastic disks acted as the medium to support the biological growth. The British Patent 930,226 issued to Hartmann(1772) was based on this design, and the successful operation of the experimental plants at Stuttgart and at Heilbron in Germany has also been described (1770). More recently, Joost (2350) reported in general terms on a similar system called the "Rotating Biological Surface" waste treatment process. Although he cited the advantages of the system, he did not give sufficient data for design purposes.

Power costs for this type of plant have been shown by Allen (38) and Joost (2350) to be low compared to other biological systems. Using a two-stage system, Hartmann(1773) stated that mixtures of sewage and trade waste waters have been treated with 60% removal of BOD by the dipping contact filter. Joost (2350) concluded that 90% of the BOD could be removed from domestic waste with a retention time of less than 45 minutes. In an effort to reduce costs and odors, Schreiber (3891) developed a type of dipping contact bed which allowed the medium to move for periodic cleaning. In the "Proceedings of the International Congress PRO AQUA 1961," Stengelin reviewed the design and operation of dipping percolating filters and their advantages (4208).

Critique

A critique of the contact bed information may appear superfluous since this system has essentially been phased out of waste treatment plant operations due to its low capacity treatment. However, due to the recent renewed interest, the following comments regarding dipping contact filters are made.

Dipping contact filters have not enjoyed wide popularity, even with the work of Buswell in the 1930's, Schreiber in 1940, Hartmann in the 1960's, Stengelin's review in 1961, and Joost in 1969. Since the technique was known and studied, it would appear that conditions were not favorable for its use. Other systems, such as the trickling filter or the activated-sludge process, must have definite advantage, since their use is increasing and is preferred. The application of the dipping contact system has been limited to rather unique problems. The operating difficulties and the nuisance factors suggest that the economics of the application be carefully evaluated. In Mr. Joost's paper, which was written for the purpose of informing designers of the technique, necessary operational data are missing. For proprietary reasons, the economics of the technique were not revealed and at his own suggestion the capital cost of the system, also not given, should include an enclosure device to protect the biomass on the rotating disk from interference by windstorms, hail or heavy rain. A highly favorable design characteristic is the low personnel requirement of this system.

Conventional Trickling Filter Systems

The term "conventional" means a treatment plant employing trickling filters in a commonly used fashion, i.e., after primary treatment and followed by secondary clarification. Thousands of these plants utilizing trickling filters have been built (4916) and their design, construction, operation, and problems described. Typical of the literature are papers such as the sewage plant for Leominster, Massachusetts, (population 4,000) built prior to 1919 (5314) and recent reports for the plant at Magna, Utah, (2722), and Greensboro, North Carolina, (5644), both built in the early sixties, which incorporated trickling filters in the sewage treatment plant.

Pearson (3328) in 1965 listed design factors which, generally, are in agreement with those described by Chase (658) in 1945. These factors are summarized as follows:

1. Pretreatment - The solids-liquids separation to reduce the clogging of filters in the form of primary clarification by some type of sedimentation, screens, preaeration, prechlorination or other methods is viewed as extremely important. It is noted that fine mechanical screens were installed at Akron and Baltimore between the primary settling tanks and the filters to intercept clogging materials.

2. Loadings - The loadings on the trickling filter are expressed in the terms of a volume of settled sewage applied per day and pounds of oxidizable material per unit area or volume applied per day. Chase expressed the opinion that the use of BOD as the sole criterion for filter loading did not seem correct, as it did not consider nitrification.

3. Depth of filters - The depth of filters was viewed as significant from the standpoint of nitrification, and limited land area favored deeper filters. It was further noted in the case of two-stage high rate filters that filter depths of only three feet are used.

4. Filter media - One of the most important considerations in design is the selection and placing of filter media. Chase's comments, published in 1912 (655), are essentially applicable today, such as the stones used were nearly cubical with rough (not porous) surfaces and not susceptible to deterioration. The sizes of the stone were from 1.5 to 2.5 inches diameter for standard rate filters and 3 to 4 inches diameter for high-rate filters. The uniform distribution of the sewage over the surface of the filter by fixed spray nozzles contributed to the practical application of trickling filters to the purification of sewage.

5. Dosing methods - The limitations for using six spray nozzles are noted. The technique of intermittent dosage as used in 1945 is significant in aiding the ventilation requirements of the filter. An advantage of continuous application is the reduction of the fly problem.

6. Ventilation - The evidence from forced ventilation and natural ventilation, as well as freely ventilated walls and enclosed walls, indicated to Chase (658) that neither forced ventilation nor porous filter walls are essential, provided there is adequate underdrain ventilation.

7. Underdrains - Of several types of underdrainage systems which have been devised, any system is adequate which provides prompt removal of the filtered sewage and allows ventilation between the top surface of the filter and its undersurface. The system must have sufficient capacity to permit easy inflow and outflow of air and to provide sufficient velocity of the effluent to prevent accumulations of sludge and grit.

8. Post-treatment - Due to the sloughing phenomenon, a final clarifier is required to separate the settleable solids from the purified effluent. The secondary sedimentation could be intermittent sand filter, a filter with a settling tank, or other means. Chlorination is used for bacteria removal.

9. Recirculation - The evidence available to Chase on the most advantageous combination for recirculation is inconclusive, but the trend has been established to use recirculation on standard rate as well as high-rate filters. There is much evidence that recirculation is of considerable value.

Papers were published (589, 893, 1870) which are typical of many indicating the modes and trends of biological trickling filter usage. Design information is available in Imhoff's handbook (2176), yet investigators have always demonstrated a curiosity and a desire to improve their design procedures (4793).

High-Rate Filters

There is no rigid dividing line between the various rate trickling filters, as may be noted from the literature (274, 658, 1563, 3071, 4916). However, some rather general ranges are given in Table I to differentiate the various types of trickling filters by the hydraulic and the organic loadings. Greeley (1563) reported that high-rate filters are operated with organic loads in the range of 50 times the normal load for the low-rate (standard rate) trickling filters. The development of high-rate trickling filter systems generated a few patented processes (807).

Table 1

Design Comparison of Different Rate Filters[a]

	Rate		
	Low	High	Super[b]
Hydraulic Loading			
gallon/min/ft^2	0.0175-0.07	0.139-0.7	1-6
gallon/ft^2/day	25-100	200-1000	1440-8640
million gallon/acre/day (mgad)	1.1-4.4	8.7-44	62.5-455
Organic Loading			
lb BOD/1000 ft^3/day	5-25	25-300	126-1512
lb BOD/acre-ft/day	220-1,100	1,100-13,000	5,360-64,320
lb BOD/cu yd/day	0.137-0.68	0.68-8.1	3.32-39.9

[a] See references 538, 1697, 4916 and 5574.
[b] Also referred to as roughing filters.

High-rate filters are of three principal types, depending on rate of feeding, recirculation or loading. The three types are the Biofilter, the Accelo-Filter and the Aero-Filter.

Jenks (2305) described the Biofilter plant as comprised of essentially one or more detention tanks, a similar number of filters, relatively shallow and arranged for stage working, and a recirculation system. A Biofilter (5574) usually has the media about 4-5 ft deep, and utilizes recirculation. Organic loadings are of the order of 2,500-3,000 pounds of BOD per day per acre-foot (57.5 to 69 lb BOD/1000 ft^3/day) based on the strength of the primary tank effluent, with hydraulic loadings ranging from 10 to 30 mgad (230 to 690 gal/ft^2/day).

The Accelo-Filter (5574), which is relatively deep, has direct recirculation of unsettled filter effluent back to the inlet of the distributor. Organic loadings, based on the organic content of the primary tank effluent, are in the same range as the Biofilter, of the order of 2,540-3,000 pounds of BOD per acre-foot per day (55 to 69 lb. BOD/1,000 ft^3/day, or 1.5 to 1.9 pounds per cubic yard per day). It has been described (1563) as accelerated biological treatment by direct recirculation of large quantities of material to a rotary distributor on the biological filter. Gillard (1474) reported that this system may be operated as either a high-rate or a conventional percolating filter.

Much of the basic work published by Halvorson et al. (1665) led to the development of the Aero-Filter, which has a relatively deep media bed of six to nine feet. This system (5574) utilizes a low momentary rate of sewage application by means of a special distribution apparatus designed for "rain drop" application over a maximum area of the filter at one time. Recommended organic loadings are from 3,000 to 3,200 pounds of BOD per acre-foot, or 1.9 to 2.0 pounds per cubic yard per day (69 to 73.6 lb BOD/1,000 ft^3/day), and the hydraulic loading rate (1563) is more than 10 mgad (230 gal./ft^2/day) with recirculation if necessary to maintain this rate. Flowthrough diagrams are shown in Figure 4, page 90, illustrating the versatility of the recirculation systems.

The development efforts by Hamlin (1697) culminated in the super-rate filter (see Table I and section on "Roughing Filters"). This high-rate filter has a very shallow bed (one foot) and is dosed at hydraulic loading rate as high as 455 mgad (10,465 gal./ft^2/day). Hamlin says, "With a BOD removal of 9,000 lb in the preliminary units and the super-rate filter the power requirements were some 80 hp and a BOD removal of 6.25 lb per kilowatt hour with a 60 percent removal of overall BOD." With the advent of the plastic era, lighter prefabricated materials were substituted for the heavier inorganic materials used as media in pilot and sewage treatment plants (488, 538, 678, 1083, 1106, 1120, 2955, 3329). With this change, high-rate filters were successfully operated at hydraulic loadings from 62.5 to 375 mgad, (1437 to 8625 gal./ft^2/day) and organic loadings from 5,000 to 64,000 lb of BOD per acre-foot per day (115 to 1472 lb BOD/1,000 ft^3/day). The advantages of plastic media are removal of high BOD at high hydraulic loads; light weight, requiring less support structure and thus less cost; and freedom from corrosion.

In establishing the design criteria for the hydraulic loading rate, Eliassen (1150, 1154) developed charts to facilitate the determination of the filter capacity based on gallons of sewage per acre-foot per day or pounds of BOD applied per cubic yard per day. As one of many investigators, Imhoff (2211) was concerned with the difference in loading between low-rate and high-rate percolating filters, and suggested that to ensure the necessary cleansing action the surface load should not be less than 27.4 ft^3/hr. The depths of the German filters were reported (2211) to be not greater than 10 to 13 feet. Schulz (3910) operated an experimental tower percolating filter, 26 feet deep, which had forced ventilation, at a hydraulic load of 15 cubic meters per cubic meter of media per day (4.9 mgad or 113 gal./ft^2/day).

Bachmann (133), in his review of the design and operation of the Biofiltration system, noted that if the hydraulic rate exceeded 100 to 125 mgad (2,300 to 2,580 gal./ft^2/day) flooding would occur. According to Bogren (383), cotton finishing waste liquors, which have been treated previously by a standard trickling filter, have been studied in a pilot plant with a high-rate percolating filter. Greater reductions in BOD were realized when operating at 10 mgad (230 gal./ft^2/day) than with a low-rate filter.

Organic loads in excess of 1,000 lb BOD/acre-foot/day (23 lb BOD/1,000 ft^3/day) were used at ninety military installations and as many municipalities in 1948 (1567). An upper limit on the applied organic loading was calculated by Greeley et al. (1566) to be 10,000 lb/BOD/acre-foot/day (230 lb BOD/1,000 ft^3/day). The load-efficiency relationship is affected by local factors such as treatability of the sewage, temperature, etc. German experience (376, 2185, 3785), over a period of more than 24 years, showed successful use of the high-rate filter, even though the waste was more concentrated than U.S. sewage. Rankin (3502), in his analysis of operating data, found the effect of organic load on the efficiency of Biofilter plants is primarily dependent on the ratio of recirculation. Dosing rate, loading of filter, or depth of filter have no significant effect in the range covered by the data. Homack, in the discussion of the paper by Rankin (3502), and Pearson (3328) were among many of the investigators who stated that the waste character was a critical factor in the design of high-rate trickling filters. High-rate trickling filters have been used for many industrial waste waters with high organic concentrations, for example, by Reimers et al. (3551) for fine chemical wastes, by Mercer et al. (2972) for liquid canning wastes, by Burns and Eckenfelder (538) for pulp wastes, and by Pearson (3328) for a variety of wastes.

Critique

After the first use of the trickling filter at the Lawrence Experiment Station of the Massachusetts Board of Health in 1889, studies at the pilot plant stage and of operational data showed the way for necessary improvements in design, materials of construction, and operation. The advantages of a high-rate trickling filter, along with the governmental sanitary requirements, provided the necessary stimuli for the adoption of the system for urban and industrial sewage. Foreign work was often reported dealing with high-rate or high-capacity systems, and, after conversion to units familiar to the U. S. figures, the loadings were not always in the high-rate range. This simple fact may well have been, and still is, a problem in the communications of performance factors. Thus, it has been stated that the super-rate filters being used today in many applications have hydraulic loadings of 1 to 6, whereas low-rate filters had loadings of 1 to 4. The difference is, of course, the units. The super-rate filter is expressed in gallons per minute per square foot cross-sectional area and the low rate filter is expressed in millions of gallons per acre of area per day. To be consistent, the filters should be expressed in the same units, e.g. 62 to 455 mgad for the high-rate and 1 to 4 mgad for the low-rate loadings.

Low-Rate Filters

The low-rate or standard trickling filter was the backbone of the secondary biological treatment process for nearly 50 years and many are still in operation today (2504, 4358). As late as 1950, the standard rate trickling filter represented more than 50% of all secondary treatment works (4358). The hydraulic and organic loadings of the low-rate filter are indicated in the ranges as shown on Table I. The low-rate trickling filter was described as being from 4.5 to 6 feet deep (4596, 5574). The rock media varied from 1.5 to 2.5 inches nominal diameter and was dosed with fixed nozzle distributors and, later, rotary distributors (658, 3327, 5574). Low-rate filters commonly had a dosing period of 3 minutes and a rest period of 6 minutes (658), which was a topic of considerable controversy (4187). The underdrains were sized to flow half-full at the designed flow for adequate ventilation (3501). A primary difference in the low-rate and high-rate filter system was the degree of nitrification achieved (1029). The low-rate filter, having a greater detention time and lower hydraulic and organic loading, produced a more highly nitrified effluent than the high-rate trickling filter (1029, 1150).

Most of the recent published work has been on the high-rate rather than low-rate trickling filter system (1542, 1559). Grantham (1542) reported on the operation of standard rate design filters that were operating at an overloaded condition. These filters were described as intermediately loaded systems. The hydraulic loading of between 5 and 20 mgad (115 to 460 gal./ft^2/day) on 6-ft deep filters places this operation in a gray area between low-rate and high-rate filters, as indicated in Table 1. It was concluded that organic loadings of over 2,500 lb BOD/acre-foot/day (575 lb BOD/1,000 ft^3/day) and hydraulic loadings greater than 10 to 12.5 mgad (230 to 288 gal./ft^2/day) should be avoided. However, Grantham (1542), based on studies by others, stated that standard rate filters operated in excess of their design loading without recirculation may be expected to reduce BOD with little or no decrease in efficiency and without operational difficulties. The nitrification of the filter effluent was reported to decrease as the organic and hydraulic loading increased. Lanz (2629) tested the hydraulic loading incrementally up to the rate of 30.5 m^3/m^2/day (748 gal./ft^2/day) in a 3-meter (10-feet) deep filter (approximately 10 cubic meters sewage per cubic meter media, 3.3 mgad). He found that the efficiency of the filter decreased with increasing load, but even at the highest rate tested the effluent was not putrescible. Aeration at a rate of 30.8 yd^3/hr (23.5 m^3/hr) was sufficient to maintain the biological purifying power at maximum load studied.

Typical of the transformation which took place in trickling filter design was the conversion of the Black River Sewage Treatment Works, Baltimore, from low-rate filters to high-rate filters. Keefer and Meisel (2404), in rechecking results obtained in 1938, verified the earlier work. By increasing the hydraulic load from 2.68 to 16.39 mgad (62 to 377 gal/ft^2/day), the resulting BOD removals were in the 90% range at the low rate (2.68), in the 80% range up to 13.53 mgad (312 gal/ft^2/day), and about 70% at the 16.39 mgad rate.

Critique

In the gradual development of the low-rate trickling filter into a high-rate trickling filter, there was a good understanding of the many factors which influenced the operation and efficiency. However, one point which cannot be overlooked is the degree of nitrification. It was thought for many years that the early treatment plants were operating most efficiently when the degree of nitrification was the highest. In England, nitrate measurements were made originally to assess the degree of stability of the effluent. It has been pointed out by many investigators that if the dilution factor of the receiving body of water is high enough, a highly nitrified effluent was not required. Cases have been reported where a highly nitrified effluent was instrumental in the development of a littoral aquatic growth. It would seem now in light of present understanding that the low-rate trickling filter would still have an application at a remote installation where the receiving stream was either dry or did not have sufficient dilution to establish a proper nitrogen balance. As will be discussed later, low-rate trickling filters with slight modifications and in series operation with other units have found limited application. Walton's paper (4596) is very indicative of the slowness of adopting new technology of a proven process to develop more efficient waste treatment systems. It must be remembered that this conservative approach, or absence of innovation, which has been demonstrated time and again throughout the history of trickling filter waste treatment, was predicated upon the heavy responsibility placed upon those controlling the change. This responsibility to the public, and the operation of the sewage plant with limited funds and manpower, nurtured the replication of known and proven technology. For changes to take place on a widespread basis, exhaustive experimental data were required as a safeguard to the populace. Today, this responsibility still exists, but changes in technology are more easily acceptable.

Single-Stage Filters

The single-stage trickling filter was the unit most commonly employed (with low-rate designs) during the early development of the biological filtration technique (4358). It has been described (5574) as being 6 to 10 feet deep, filled with various media, usually a crushed rock or slag, and followed by a clarifier (4358). Single-stage filtration appeared inferior (2118, 3551, 4804) when its performance was compared with two-stage and alternating double filtration techniques. In many of the comparisons (35, 3260), two-stage and double filtration operated with less difficulty and gave a better quality effluent. Hansen (1719) concluded that single-stage trickling filter treatment has been found unsatisfactory for strong sewages.

Jenks (2305) discussed the advantages and costs for a single-stage, as well as for a two-stage, trickling filter plant by operating with much higher rates of recirculation, the technique of which was developed into the commercial Biofilter process. The hydraulic and organic loadings on the single-stage filter were determined usually by local factors and the effluent requirements (3161, 4538). Meltzer (2965) stated that there is no evidence that two-stage processes are any more efficient than single-stage filtration in deep bed filters. Escritt (1204) commented that filters operating by single filtration should be as deep as practicable. The American Society of Civil Engineers (4912), in a review of sewage developments during 1944 and 1945, and based on a review by Chase (658), stated that the medium for a single-stage filtration is usually 6 to 10 feet deep, whereas the high-rate filter may be 5 feet for a single stage and 3 feet for two stages.

Design charts were prepared by Baker and Graves (150) for single-stage filters using several design formulas. Data were reviewed and interpreted by several investigators (85, 352, 1233), in which the performance of single-stage operation was studied in detail, and it was shown that organic and hydraulic loadings, recirculation, and temperature have non-linear effects on performance. In addition, the cross-product terms in their analysis indicated that these variables are not independent in their effects (352). When performance was evaluated as a percentage of BOD removal, the effect of the strength of sewage applied to the filter was negligible (1233). Archer and Robinson (85) related the efficiency of a single-stage filter with media volume and recirculation ratio based on performance formulas of the National Research Council and compared them with field performances. Predictions of efficiencies using charts and formulas were found to agree closely with field performances. Recirculation improved the overall efficiency of the plant. Montgomery (3074) discussed the results obtained at various plants where the single-stage Aerofilter has been used, and Fischer (1285) discussed the Biofilter principle from the standpoint of the effectiveness of a single-stage application. Both reported that between 70 and 80% BOD removal was expected when the recirculation ratio is 1.5:1, although as high as 87% BOD removal has been obtained.

Typical of the many applications of single-stage filtration was that reported by Imhoff and Dahlem (2204) for a small town waste treatment system, but they cautioned that the low rate of flow created problems due to odors and flies. The nuisance problems are reduced by filtration at a high rate with recirculation of the effluent. At the recently constructed sewage treatment plant at Aylesbury, England, (4940), the filters were flexibly designed to operate by single-stage filtration among other schemes. Water quality was good enough that the final effluent could be discharged directly into the River Thames or used for irrigation. Other single-stage applications were, typically, treatment of hospital wastes (3912), rubber processing waste waters (3055), and the combined waste waters from a paint works, creamery, foundry, laundry, malt processing, and domestic sewage (4582).

Critique

The literature has indicated an awareness by the investigators that, although the single-stage filter is adequate and satisfactory, increased detention time or two-stage filtration, which achieves essentially the same thing, was required. Limitations of the increased depth were that the media may not be able to support a very deep bed and required a significant foundation structure. Modifications of existing installations of single-stage units were often forced by economics to expand the plant by adding a second-stage filtration system to compensate for the added depth required for sufficient BOD removal. Media other than rock could have been used, but acceptance of these other media was slow. With the development of media which were lighter weight and possessed proper ventilation characteristics, single-stage installations using deep beds were again considered. Montgomery (3074) noted that, although it was possible to improve single-stage filtration by parallel recirculation, the process was not economical in this situation as it was cheaper to use two-stage filtration when a high degree of purification was required. In all probability, this statement is still true today, with the exception that the two stages need not both be trickling filters. The "acid test" would appear to be the projected costs of removal of a pound of BOD per day over a twenty-year period for both systems.

Two-Stage Filters

Two-stage or double filtration means two biological trickling filters in series with or without intermediate clarifiers, followed by final clarification. This technique was a natural development for overload plants, as suggested by Nelson (3159). The increased popularity of high-rate trickling filters since 1944, with two-stage operation to maintain effluent quality, developed different design criteria (1915). Different international trends were established. The U. S. favored two-stage treatment in shallow high-rate percolating filters with elaborate provisions for recirculation. Great Britain favored two-stage treatment and relatively deep percolating filters at more moderate rates with the added condition of being able to interchange the sequence of filtering units (1719).

Sorrels and Zeller (4111) investigated the design factors involved in the operation of two-stage trickling filters with and without intermediate sedimentation. Archer and Robinson (85) and Germain (1460) concurred with Sorrels and Zeller that removal of the intermediate clarifier did not harm the treatment plant efficiency. Meltzer (2965) suggested the so-called two-stage operation is, in actuality, a single-stage deep bed from the efficiency viewpoint. Brown (492) stated that the cause of an odor problem was due to an inadequate temperature differential between the waste waters and the atmosphere, which inhibited natural ventilation. Introduction of forced ventilation solved the odor problem and improved the operating efficiency of the plant. Whitehead (4711) suggested for design purposes that, when the influent BOD does not rapidly increase, trickling filters alone would probably give adequate treatment.

Montgomery (3074), in discussing the results obtained on an Aero-Filter at Austin, Minnesota, calculated the removal of BOD using the same volume of medium and concluded that shallow filters give inferior results when recirculation is not used, but the increased amount of recirculation required to maintain the minimum flow per unit area on the shallow bed compensates for its lower efficiency. Recirculation ratios from 1.5:1 up to 6:1, in the two-stage process, have been used by Fischer (1285) and by Jenks (2305), depending on the local conditions and operating techniques required to render the effluent acceptable. Archer and Robinson (85) reported that the slight differences in medium volume between first-stage and second-stage had a very limited effect on the overall efficiency, to have the volumes equally divided between the two filters and the recirculation equal for both stages. Smith and Wittenmyer (4086) reported on the use of the plastic media, Surfpac®*, as the first stage in a two-stage filter system to take advantage of existing percolating filters to increase treatment capacity.

Remote locations, such as turnpike rest areas, have been serviced by two-stage biological filtration (977). Bowes (426), forty years ago, noted that small installations were equipped with two-stage filters and identified the auxiliary equipment and manpower required. Package treatment systems using the two-stage approach were available in eight sizes and operable with little or no attention (5118).

Municipal applications of two-stage trickling filters number in the low thousands (4916). Typical of these are installations at Oklahoma City, Oklahoma (930), Suffern, New York (5411),

---

*A registered trademark of The Dow Chemical Company.

Newbury (5226) and Aylesbury (4940) in England, and Walvis Bay (3700) in Southwest Africa. Many other two-stage biological systems have been installed and operated and will be discussed later under sections emphasizing other factors.

Industrial waste applications of two-stage trickling filters are numerous. For instances, the treatment of chemical waste (3551), combined sewage and milk waste (4804), meat packing house waste, in combination with other processes (1959), as well as many more, are described and referenced under their specific wastes in Part IV.

Of the many mathematically oriented papers (most of which are discussed elsewhere) dealing with two-stage trickling filters, design is discussed by many, including Archer and Robinson (85), Wishart (4793), and Baker and Graves (150). Wishart expressed the opinion that there were discrepancies between actual BOD effluent data and BOD values calculated from the National Research Council (NRC) formulas. Archer and Robinson, through additional studies, found that the National Research Council formula predicted quite closely field performances which were obtained in a newly constructed two-stage biological filtration system. Later, Baker and Graves suggested modifications of other formulas for second-stage filters to closely follow the National Research Council formula and presented design charts for each, with a computer program to optimize the two-stage filter volume.

Critique

The literature on two-stage trickling filter applications showed that this development grew out of necessity from overloaded conditions at treatment plants. As noted previously in the discussion on single-stage filtration, an awareness of the significance of depth and contact time was demonstrated by the investigators who were active in the pre-World War II period. Once the stresses of war were removed and the data resulting from the operation of the military two-stage trickling filter plants could be observed, more reliable predictions were incorporated into the design of new systems. Many times the development of a two-stage plant was governed by factors other than the optimum hydraulic or biologic information. For instance, if the existing single-stage trickling filter unit was equipped with media of sufficient volume and the waste was of low BOD strength, this trickling filter could be used as the first stage in a two-stage system. The second stage could be another trickling filter or, if the regulatory agency required a very high effluent quality, the activated-sludge process. Another example would be an existing single-stage biological filter with a relatively small medium volume and an influent waste of significant BOD which was operating under an overloaded condition. The solution to this problem could have been the installation of a two-stage trickling filter plant. With the development of media other than rock, in the last 10 to 20 years, the use of a roughing filter ahead of the existing trickling filter has been a popular practical solution. If the waste was fairly uniform and a high enough BOD, an activated-sludge unit may have been installed ahead of the trickling filter, converting the existing trickling filter into a polishing filter. The design engineer had at his disposal several options which were dictated by local conditions and regulations at the time of design. It is anticipated that overloaded conditions will also be rectified in the future by two-stage trickling filter operation.

Three-Stage Filters

In present day terminology, three-stage or tertiary treatment usually connotes activities concerned with pollution control of nutrients, primarily phosphorus and nitrogen. However, three-stage biological treatment was practiced more than 38 years ago by Rhode (3582) who fitted brown coal slag filters with perforated clay pipes for better aeration to treat waste waters from a dye works. Dibdin (946) concluded in 1910 that tertiary waste treatment may be necessary in exceptional cases and recommended sand filters, land irrigation, fine contact beds, and percolating beds. Packing house wastes were treated by Howson (2071, 2072) in a fashion similar to that described by Rhode (3582), but the primary trickling filter was equipped with a compressed air supply and wash water and was operated at a hydraulic load of about 6 mgad (138 gal./ft^2/day). The two final filters were (2071) loaded at about 1.4 mgad (32 gal./ft^2/day), handling a waste which had 1,000 mg/l BOD and after primary filtration was reduced to 250-350 mg/l BOD. The effluent resulting from treatment of packing house waste with a BOD of 1,500 mg/l in a three-stage process could be reduced by 98 to 99% (2072).

Pharmaceutical and other fermentation wastes have been treated with a three-stage treatment system (952, 3058). Quite often with these systems it was desirable to have an activated-sludge unit included in the process (952, 956). Patented equipment, such as that proposed by Dekema (914), often is composed of multi-stage filtering units with various types of enclosures and aerated sections to minimize the nuisance problems and yield an efficient process. Meltzer (2963) stated that tertiary filtration may be 80 to 100% superior to double filtration, based on hydraulic advantages.

Critique

The treatment plant involved in a three-stage trickling filter process requires high capital investment, so that either biological or nonbiological waste treatment could be used. For economical trickling filter use, local topography should provide sufficient head (6 to 10 feet per filter) or pumping costs must be included. A factor in favor of the three-stage system is the development, under heterogeneous microorganism population conditions, of selected strains of microorganisms in each filter stratum. The microorganisms can cope with the influent environment of a complex waste stream and survive the shock of a strong sewage. With rock medium, a three-stage trickling filter system would have sufficient medium depth and thereby provide a long detention time of the waste water on the biological film. With the development of media other than rock (e.g. plastic), deeper beds have been constructed with the resulting longer detention time. One should consider, however, that once the biological film has sloughed from the media, biological activity does not stop. The activity of the microorganism population, while contained in a clarification tank, has been demonstrated many times, and even the casual observer has seen the rising solids in the secondary clarifiers. Yet, Sorrels and Zeller (4111) and Archer and Robinson (85) reported that intermediate clarification had negligible effect on efficiency. Therefore, in a three-stage biological filtration treatment system, intermediate clarification may not be necessary.

Alternating Double Filtration

Alternating double filtration has been described by Hurley (2110), Rumpf (3782), Calvert (593), Whitehead (4712), Escritt (1194), Daviss (891), and others, as a two-stage biological trickling filter operation which is arranged in such a manner that the order of the primary and secondary filter may be interchanged periodically. In a discussion of the paper by Whitehead (4712), D. M. Watson stated that surface clogging of the trickling filters was avoided by this process. In reviewing the development of recirculation, deep aerated covered filters, and alternating double filtration systems, W. Watson (4640) suggested that, when alternating double filtration was employed, dissolved oxygen in the primary filter effluent caused sloughing.

At the same time that the high-rate biofiltration type processes were being developed in the United States alternating double filtration systems were being employed. Hurley (2118) reviewed O'Shaughnessy's observation (3253) that a clogged filter could be restored by dosing it with partially purified sewage or filter effluent, i.e., alternate the first and second stage recycle. For maximum efficiency (2118) it was recommended that each part of a filter should always carry out the same type of work, which does not occur in the process of alternating double filtration. He suggested that greater nitrification would be obtained if other means were used for keeping the surface clean, e.g., by using coarser medium in the surface layers, or by covering the filter so that scavenging organisms would come to the surface and destroy the slime. With alternating double filtration, satisfactory results have been obtained with doses of 150 to 200 gal. per cu yd per day (2121). Filters operated by alternating double filtration do not require as deep a bed as single-stage filtration beds, according to Escritt (1204). With the high-rate and alternating double filtration systems available, Herriot (1899) decided the selection of the processes for the wastewater treatment from an economic standpoint. Discrepancies in using the National Research Council formula for calculating effluent BOD values on alternating double filtration systems were pointed out by Wishart (4793).

The alternating double filtration system was applied mainly in countries other than the United States. Belgium (4352), England (891, 4940) and other European countries have found the system satisfactory. In recently designed plants (179, 891, 4352, 4940), alternating double filtration and recirculation of effluent have provided flexibility in operation. Waste stream from tanneries, gas works, dairies and other industries have been treated satisfactorily by using alternating double filtration (35, 3121, 4804, 5446, 5522). In treating the tannery waste (35), alternative systems were tested, and the results of the systems were judged by the degree of nitrification achieved with alternating double filtration being the best, contrary to Hurley's doubts (2118). The effluent from the alternating double filtration plant at a dairy in South Africa was used as cooling and boiler feed water (5446). Alternating double filtration in the United States, such as at Marysville, Ohio, (4804), has occasionally treated combined sewage and dairy waste with satisfactory results.

Critique

Alternating double filtration was quite common in Great Britain and other parts of Europe, while the application in this country has been limited. This limited application may be due to economics, since many of the two-stage biological filtration plants were built to operate by gravity flow and a major modification would be necessary to install sufficient pump capacity to reverse the order of the filters. At the same time, the development of the high-rate (biofiltration type) trickling filter process approximately paralleled the development of alternating double filtration. The high-rate filtration process was an American innovation, while alternating double filtration was chiefly promoted by the British. For conditions which may exist in a waste stream which cause troublesome biological growth (e.g. high carbohydrate waste), alternating double filtration has an application.

In essence, in this process the filter is being rested and washed by running the secondary effluent over the primary filter and vice versa. The operational technique of resting and rinsing has been used in England, this country, and others for scores of years. In some of the early work reported by Jenks (2305) and Halvorson (1667), plugging problems were overcome by an increased rate of recirculation. This recirculation, which lowered the organic load and raised the hydraulic load, may be thought of as a resting and rinsing procedure similar to alternating double filtration.

Roughing Filters

Roughing filters have been described in the book, "Sewage Treatment Plant Design," (4916) as systems used to reduce the organic load in which subsequent treatment may be applied to the effluent or where intermediate treatment is required. The design of the roughing filter (4916) differs from other filters principally because the determining factor is the volume of the waste (Table 1), as well as the high BOD of certain waste which is to be handled. Limitations in the medium available for use in roughing filters were overcome by considerations outlined by Pearson (3328). Roughing filter design required (3328) an open flow pattern which allowed the unhindered flow of the microorganism-waste stream down the medium column and encouraged uniform distribution of this flow. Organic loadings on these filters have been reported (1029) to vary from 5,000 to 20,000 lb BOD/ac-f/day (115 to 460 lb BOD/1,000 ft^3/day). Recirculation was normally practiced to maintain efficiency and keep the biological film in a wetted condition (681, 1029). Criticism was made of the low efficiency of the roughing filter, based on the difference between the influent-effluent BOD, until efficiency was viewed as the total pounds of BOD removed per volume of medium, a quantity almost twice that of a normal high-rate filter (1029).

Roughing filters have been used for many years and their performance was published, for instance at Atlanta, Georgia, (5261), in which 12 inches of stone media with a possible rate of 175 mgad (4025 gal./ft^2/day) were used on Imhoff tank effluent. Quite often in the conversion to a two-stage trickling filter plant, the primary trickling filter was operated as a roughing filter (5470). An advantage of the roughing filter is its utility on waste streams of fluctuating strength and flow characteristics. The waste stream was saturated with oxygen in the roughing filter, but usually needed further treatment by other secondary processes (3474). A typical use of the primary filter in a two-stage operation as a roughing filter was published by Jenks (2300), during his discussion on the operation of Biofiltration systems. The super-rate filter was a type of roughing filter as defined by hydraulic and organic loadings.

In treating the waste waters from abattoirs, various forms of pretreatment were used as well as roughing filters, followed by percolating filters (3381). Hansen (1719) reported in 1944 that a routine preliminary treatment using a roughing filter could be used to decrease the organic load to subsequent processes by about 50%.

Several fabricated media, such as tiles, perforated blocks, wood lath, asbestos-cement sheets, ceramic random packings such as Raschig rings and Berl saddles, and more recently plastics, were used (3194, 5196) in roughing filters. The development of plastic media provided (681) the design engineer with an economic solution to treatment of high organic influent waste streams. Commercially available plastic media were discussed by Noble (3194) and others (98, 1083, 5196). A previous limitation of some of the fabricated media was that they were not economically competitive with conventional random packed media. However, Chipperfield (681) discussed the economics of plastic media for roughing filters and concluded that substantial (25 to 55%) savings in capital cost over conventional filters and activated-sludge plants are possible.

Critique

Most of the primary filters with plastic packing in a two-stage system may be operated at high hydraulic and organic loadings, as indicated under super-rate filters in Table 1. Many of the applications of two-stage trickling filter system, which have been reported in previous sections, involved the operation of the primary filter as a roughing filter. A description of this operation by Eckenfelder (1077) and Busch (549) was discussed in the theory section. They indicated the advantages of using roughing filters for industrial or municipal waste treatment where occassional high organic shock loads occur. Generally, it has been recommended that a roughing filter should not be used as the total treatment for an installation. It is used advantageously ahead of activated sludge and other secondary processes. The roughing filters were characterized as deep beds with media which had large void spaces and were dosed continuously, the effluent being recirculated as the operation required. The highest hydraulic loading found in the literature approached five hundred million gallons per acre per day (11,500 gal./ft^2/day). However, this high hydraulic loading rate was applied to a shallow bed filter. The depth of the roughing filter has been quite dependent upon the type of medium employed.

Polishing Filter

Polishing filters have been used in multi-stage treatment facilities to decrease the remaining soluble organic and suspended pollutants in the effluent of a conventional waste treatment plant (5574); for example, the slow sand filter (698) and intermittent sand filter (2984). However, sand filtration, which incorporated some biochemical degradation and mechanical filtration, required extensive land area per unit volume of sewage treated and was, therefore, replaced by other systems, as described by Metcalf and Eddy in their book on "Disposal of Sewage" (2984). The influent waste from a population of 2,500, or a flow of 250,000 gpd, is considered the maximum to be handled by intermittent sand filtration (4916). For polishing filters, a crude type of trickling filter was recommended by Dibdin (946) and trickling filters, following partial treatment by aeration, were reported by Thomson (4380) to handle waste flows in Great Britain. In the two-stage operation, as previously discussed (1719), if the primary filter is considered as a roughing filter, then the secondary filter is a polishing filter. This application has more significance in design consideration than semantics, as indicated by Bryan (516), in using polish filters on industrial waste streams. In designing a polish filter to produce a high quality final effluent, the retention time must be increased on the surface of the media. Deep bed, high specific surface area media have been used to attain effluent polishing (3328). The organic load applied to polishing filters has been reported as between 50 and 200 mg/l BOD (3328) or 900 pounds BOD per ac-f/day (20.7 lb BOD/1,000 ft^3/day). The hydraulic load may be similar to that applied to low-rate trickling filters (Table 1), between 1.1 and 4.4 mgad (25.3 to 101.2 gal./ft^2/day).

Critique

The design of polishing filters has quite often been governed by necessity rather than by choice. When an existing low-rate trickling filter became overloaded, quite often the procedure has been to insert ahead of it a high-rate trickling filter or activated-sludge system. With most of the organic load being removed and the flow being buffered, the low-rate trickling filter would remove a major portion of the remaining BOD and result in a stable effluent. This was shown to be a very economical solution, since the existing physical plant was used.

Contact Aeration

Contact aeration is an aerobic process whereby the supporting medium is covered with the biological film under submerged conditions and aerated by compressed air (p. 193 of 4916). This system was first suggested by Buswell, according to Metcalf and Eddy (2984), to satisfy a need in waste treatment somewhere between trickling filters and activated-sludge plants. The use of this technique was common in the late 1920's and early 1930's in this country and abroad (3150, 4037). A typical contact aerator (2984, 5364) is a tank with a false wood bottom, consisting of 2" x 4" planks set on edge with 0.75-inch slots between them to allow the air to rise through a coke filling. The coke was kept in place by a galvanized steel wire mesh one inch square, and a layer of broken limestone 2 inches thick over the mesh prevents the coke from floating. Other systems were available (3864) which used movable wooden bodies of small volume but large surface. Aeration systems were described, typically, designed by Passavant (3307), with primary emphasis on the distribution systems. Hydraulic loadings were reported (2984) to vary from one-half to two million gallons a day with contact periods of from 10 to 90 minutes. During World War II, the contact aerator treatment system was installed at many of the military installations, but the results were not altogether satisfactory. The American Society of Civil Engineers Manual of Engineering Practice No. 36 (4916) stated in 1959 that ... "The contact aeration process has not been widely accepted and there are few published operation data."

Critique

The application of the contact aerator has been sporadic. Goldthorpe, in discussing Chipperfield's paper (674), wondered if plastic media had been considered in the application of a tauchkörper, which is a contact aeration system. The system may have an application in present day usage. However, one should be aware in operating a type of activated-sludge plant without a high degree of control of the biological solids that operating problems would arise. The design of this system without more available data would require experimental investigations. The advantages of the contact aerator process are: (a) its ability to hold a quantity of microorganisms even through a shock load of toxic or high organic waste (detrimental to part of the biopopulation), (b) minimum problems with distribution, (c) little freezing, and (d) control of odors and other nuisances. Cleaning the media would be a disadvantage in maintenance. Based on experimental investigations, however, it is entirely conceivable that this hybrid between the trickling filter and activated-sludge system could be designed to optimize the strengths of each system and minimize the weaknesses. Qualified operators would have to be available.

MULTI-UNIT SYSTEMS

The review and discussion of multi-unit systems provide additional information on the applicability of trickling filters. Trickling filters were designed to operate in parallel, in series with activated-sludge units, in series with lagoons, in series with septic tanks, and in series with Imhoff tanks and other units.

Trickling Filters In Parallel

A procedure for handling an overloaded biological trickling filtration plant either in a single stage or two stages is parallel expansion (1788, 3380). Hopper (2029) reported on the design of a waste treatment plant which was comprised of three sections of trickling filters, all operating in parallel, handling high and low level sanitary waste as well as industrial wastes. Flexible designs enabled many biological trickling filtration plants to be operated in parallel or in series, with and without circulation (1341, 3008, 5538). Operations of parallel trickling filters in colder climates have indicated high-rate filters are affected by temperature (2871). Froman (1362) described the design of two parallel plants to provide a means of testing and comparing new chemical treatments. The effluents of parallel operating portions of the biological filtration plant are mixed and further treated before discharge (3380).

Critique

Trickling filters in parallel were a design concept which was used (4223) to handle plant expansion, overloaded conditions, specialized waste problems, and other requirements which would be satisfied by having an additional plant operating alongside an existing facility.

Further comments are found in preceding critiques on single-stage, two-stage, high-rate, and low-rate trickling filters.

Trickling Filters and Activated-Sludge Process

Trickling filters and activated-sludge units have been used in sewage operations to overcome the limitations of each process. Prüss and Blunk (3474) indicated that the main disadvantage of the activated-sludge process is its sensitivity toward the variations in the sewage and this sensitivity is overcome by pretreatment on trickling filters. According to Ball (159), when trickling filters and activated-sludge units are used in series the plant capacity is increased. Also, where there were large seasonal variations in the population served, the activated-sludge process alone or in combination with percolating filters is most economical. Installations receiving peak loads of brewery (4583), textile (2037), and paper wastes (1449) have successfully used a combination of trickling filter and activated sludge. When the activated-sludge process preceded biological filtration, Sickert (4013) found that not only was clogging prevented, but also the efficiency of the plant was measurably increased. In the discussion of Whitehead's (4711) paper, Watson (4712) was a proponent of the use of preliminary treatment by activated sludge to avoid clogging of the surface of trickling filters. However, Whitehead (4711) stated that bioflocculation followed by trickling filter treatment was more economical and effective than either activated sludge or trickling filter alone. Emde (1168) cites the advantage, where high purification is required, of using series operated percolating filters and activated sludge. Ball (159) and Fischer and Thompson (1279) indicate that when there are large variations in the flow, or when an activated-sludge plant is overloaded an economical approach was combined trickling filter - activated-sludge operation. This approach in handling an overloaded situation was supported by Hurley (2108), Garner (1416), and Allen (35).

Various wastes were treated effectively with combined activated sludge - trickling filter operations in Germany (4013), England (4583), Belgium (640), Holland (2027), Poland (1405), and in this country (956, 1449). Typical of the wastes that have been treated are the effluents from municipalities (640, 1308, 1979, 2027, 4013), chemical industry (335, 956), pulp and paper (1405, 1449, 3976), malting and brewing (1773, 4583), textiles (401), pharmaceuticals (2036), and food processing (5330). Loading and design parameters have been reported by Cauterman (640) for a population variation of 8,000 to 50,000 people, which developed a fluctuation in flow of a maximum 4,500 cubic meters per day (1.19 mgd) versus 800 cubic meters per day (0.21 mgd) minimum. The filters were designed (640) to treat the low discharge rate, with the added load beyond the capacity of the filters to be handled by a preceding activated-sludge unit in series. By using the combined system at Volksdorf, Germany, an effluent of 10-20 mg/l BOD_5 was established with waste flows up to 4,500 cubic meters per day (1.19 mgd) (4013). Hurley (2108) reported that 93% removal of the BOD was obtained in a combined waste treatment plant which had an influent composed of 40% trade waste plus sewage from 120,000 people (2108).

Bilfilters loaded with normal sewage (200-250 mg/l BOD) gave 70 to 80% removal with an effluent suitable for activated-sludge treatment, according to Fischer and Thompson (1279). Twenty-five hundred cubic meters of sewage per day (656,000 gal./day) were treated in the plant with the filters loaded at 1.2 cubic meters sewage per cubic meter filter media (90 gal./ft^3) and with the aeration time in the activated sludge tank of 1.3 hours (0.5 m^3 air/m^3 of sewage, or 1 ft^3 of air/15 gal. sewage) developed sufficient treatment. By adding settled filter effluent to primary settling tank effluent, the quantity of these effluents treatable in the aeration tanks was increased 30 to 40% (2441) with no decrease in efficiency.

Hall (1655) described the Mineola, New York, sewage plant which has five aeration tanks with a total capacity of 220,000 gallons providing five hours' retention time for a flow of 1 mgad (23 gal./ft^2/day), plus eight percolating filters, each 110 by 125 feet.

The concentration of sludge in the aeration tanks is maintained at 18 to 24% in the summer and raised to 28 to 36% in the winter. This combined waste treatment plant was treating one million gallons a day satisfactorily. Pöpel and Daser (3427) described a trickling filter - activated-sludge plant which treated the waste from a population of 70,000 in which the filters were loaded at a surface flow of eight meters per hour (26.2 ft/hr) to assure sludge washout. The aeration tanks were designed to operate under stage loadings and step aeration.

Studies by Gellman (1449) indicated that plastic media trickling filters, loaded at 100-250 lb BOD per 100 cubic feet of media (1,000 to 2,500 lb BOD/1,000 ft^3/day), would produce 50% removal with the advantage of cooling, which suggested the use of combined trickling filter activated-sludge treatment for handling the pulp and paper mill waste. Along with Gellman, Pöpel and Daser (3427) and Allen (35) used trickling filters followed by the activated-sludge process without intermediate sedimentation. Prüss and Blunk (3474) and Kershaw and Finch (2441) indicated efficient treatment with trickling filtration and activated sludge with intermediate settling. Recirculation of waste, activated sludge, clarified effluent, and mixtures thereof have been reported by Whitehead (4712), Allen (35), and Schreiber (3893) to be effective in maintaining the flora on the biological trickling filter and aiding subsequent treatment in the activated-sludge system.

Critique

The combined trickling filter - activated-sludge system is not new, but has gained some popularity recently due to higher effluent standards and other requirements. Many engineers take one side or the other, and either use trickling filters in their design or the activated-sludge process exclusively. Many studies based on the comparison of the two processes illustrate this, as may be noted in Part IV. The literature reflects the efforts of a few workers who have used the advantages of each process to solve difficult problems. It is obvious that there are applications for each process and for the combined system. A roughing tower has simplified the operation of activated-sludge plants. Fluctuations in organic load, toxicity and temperature are just a few of the factors which may be dampened by the trickling filter treatment. However, the effluent from this process will not be acceptable for discharge and many, in fact, have several milligrams per liter BOD in the final effluent. This type of effluent is ideal for further treatment by activated sludge.

Actual design criteria were not clearly defined, but trends of past experience were indicative of the size and loading of the systems. Investigators have not reported the data completely to exploit the usefulness of this concept. New construction materials, better qualified operators, more automatic control, and higher effluent standards all point to the combined trickling filter-activated sludge waste treatment plant as a reasonable solution to complex pollution problems.

Trickling Filters and Lagoons

During his thesis study on removal of low level radioisotopes, Lawrence (2642) investigated the application of biological filtration and lagoons (large shallow ponds designed for days of detention) for the removal of phosphorus-32, iodine-131, potassium-42, cerium-141 and -144, and strontium-89 among others. The results showed that primary sedimentation is relatively ineffective in removing colloidal and dissolved radionuclides from sewage, and the effectiveness of biological filtration is limited by the ability of the filter to remove the isotopes from the liquid phase and concentrate them in the solids, leaving the filter in a settleable form. The removal of radionuclides within the filter was found to be due to concentration of the nuclides by the zoogloeal slimes. Another combined waste which has been treated by the use of trickling filters and lagoons has been domestic as well as from a milk processing and poultry processing, recorded by Grewis and Burkett (1580). This plant used nutrient addition and a roughing filter and produced an effluent with 10 to 36 mg/l of BOD. Anderson et al. (73) described the biological filtration plant at Lansdale, Pennsylvania, where the effluent was treated by mechanical filtration and lagooning, and was subsequently used as cooling water for the municipal power station. Kempton and Roskopf (2428) added low-cost sedimentation lagoons after the percolating filters to give 96% BOD removal, which also raised the capability of shock load handling for the plant. A typical satisfactory operation of biological filtration, followed by lagoon treatment before discharge into a small creek, was described for a small English village (5555). However, as a step further, the installation of an Air-Aqua aeration system in the lagoons, which were used as final treatment after biological filtration in Regina, Saskatchewan, doubled the sewage capacity, as reported by Goodnow (1517).

An interesting problem in treating distillery waste in Cuba was noted by Maiz (2841), where the effluent from lagoons was further treated by two-stage biological filtration to achieve a high degree of nitrification. For the treatment of cannery waste Warrick et al. (4621) gave the details of design and operation of lagoons and the operation of lagoons in conjunction with high-rate Aero-Filters. The waste water was recirculated through the filter at a constant rate of two million gallons per day. In case of high organic loads, they recommended that the lagoons should be designed to retain 25% of the waste discharged to them. The treatment of sugar beet factory waste waters was investigated by Carruthers et al. (629). Sedimentation in lagoons alone was not a very satisfactory method, but after dilution of the waste with treated sewage, percolating filters were used with sedimentation in lagoons, both before and after filtration. The treatment of potato wastes was the topic of a symposium in 1965 (5330), and the processing waste waters were amenable to treatment by trickling filters and sewage lagoons. Treatment of phenolic waste waters was explored by Biczysko (320), using percolating filters, 14 to 16 yards deep, followed by oxidation channels (aerated lagoons), which were able to reduce phenol concentrations of the waters from 500 to 950 mg/l down to 1 mg/l.

Critique

Lagoons and trickling filters have been used for many years. Unfortunately, lagoons are very seldom properly designed and problems with odors and other nuisances are common. By storing the trickling filter effluent in lagoons, some of the nuisance conditions may be avoided. Many of the existing lagoon facilities were built as "stop-gap" methods of treatment, especially for difficult trade waste waters. Lagoons ahead of trickling filters may be used as a type of balancing tank to allow a more uniform waste to be applied to the filter. The large area requirements of lagoons are not compatible with the recent trends of less land area being used by deep bed trickling filters. As a step to decrease the land problem, aerated lagoons have been used. The aerated lagoon following the filters provides a semi-activated sludge type treatment without the advantage of controlled suspended solids or the disadvantage of sludge recycle pumping costs.

Trickling Filters And Septic Tanks

Investigators, such as Meckel (2950), reported that for farm homes septic systems, followed by either trickling filters or sub-surface disposal, were preferred early in the 1900's. Hewitt (1926) discussed the difficulties encountered in obtaining a high quality effluent at a reasonable cost. For small communities in Australia, he recommended primary treatment by septic tanks, followed by secondary treatment, using percolating filters with or without subsequent land treatment. Abbott (2) described isolated hospital sewage treatment for 7,000 people, using septic tanks with six-hour detention time and trickling filters of about one-half acre. Short detention periods in the septic tanks were reported by Kenworthy (2437), together with high dosage rate on the filter, to be responsible for the overloaded filters in Perth, Australia.

German construction of septic tank - trickling filter plants was common as early as 1898, as reported by Möhle (3035). As these plants became overloaded, a large storm water tank and sewage retention tanks were installed to improve the effluent. Wood shaving trickling filters following septic tanks were suggested by Girard (1483) in removing colloidal material, such as iron sulfide, from rural district effluent. Septic tanks and percolating filters were stated by Davies (881) to be cheap, since the low initial costs, the low manpower requirements for maintenance and operation, and an effluent of consistent quality were definite advantages. Great Britain developed standard designs (2811) consisting of septic tank and percolating filters for rural districts. The sewerage systems for air training schools in Canada during World War II took advantage of the simple operation of septic tanks followed by biological filtration, according to Langman (2620). Specialized factors in design were discussed by Subrahmanyan (4262) for percolating filters suitable for treating effluent from septic tanks in the rural districts of India.

In a discussion (5518) of a paper by Faulkner, regular maintenance of small sewage treatment plants, each consisting of a septic tank and percolating filter, but of different designs, was emphasized. Faulkner (1244) stated that treatment in septic tanks, followed by biological filtration, is suitable in most cases for sewage disposal in rural villages. Lynas (2798) reported, in 1951, that small sewage treatment plants comprised of septic tanks and percolating filters were appropriate for conditions in Northern Ireland.

After an examination of some of the small sewage works, Escritt (1206) reported that the choked condition of the filter was usually due to leaving the septic tank unsludged for too long a period of time and that the size of the trickling filter media should be at least two inches in diameter. Rolston (3683) presented a paper at the Engineering Society in British Columbia where he states that an adequate primary treatment for small communities was by septic tanks and secondary treatment by biological filtration.

Studies were carried out on the BOD loadings of percolating filters in Japan (2032) for effluents which had been given primary treatment in septic tanks. The conclusion was that adequate capacity of filters could be determined for treating domestic sewage and sewage from shops, offices and factories. Developments in the design of septic tanks and effluent treatment by biological purification through filtration in Austria were published by Lengyel (2683). He suggested passing the settled sewage through a percolating filter consisting of fibrous materials on perforated trays and separated by air spaces. Other modifications resulted in patents, e.g., Bomhoff (398). Liepolt (2718) disclosed similar work of septic tank effluent treated by fiber percolating filters. Limitations were proposed on the septic tanks by Peel (3331), in 1966, by noting that inadequate detention time, lack of servicing and maintenance, and incorrect estimate of required capacity were instrumental in yielding poor quality effluents.

Critique

Septic tanks are still popular for waste treatment at rural locations. Prior to 1930, large systems servicing cities of several thousand used septic tanks. The effluent from the septic tanks used today in modern suburban living is passed through field lines of gravel, broken rock, etc., under aerobic conditions. Basically, the system is good, but it does require proper design and regular maintenance, as many of the workers have cautioned. There are certain package plants in operation today that operate quite satisfactorily as combined septic tank - trickling filter plants.

Trickling Filters And Imhoff Tanks

Imhoff tanks, which are rectangular with an inverted pyramidal bottom and a chambering arrangement, have been used in sewage treatment in conjunction with biological trickling filters since the inception and development by Karl Imhoff, Germany. Papers by Hommon (2001), Perry (3334), Radebaugh (3499) and Imhoff (2204) are only a few examples of the extensive literature on the utilization of Imhoff tanks with trickling filters. Applications in New Jersey (5362) and in Kansas (3970), as well as in foreign countries, for example, in Brazil (1463) and Australia (5208), are also numerous. The Imhoff tank operating in series with percolating filters and sedimentation tanks has several advantages, such as economics, according to Timmerman (4394), at locations with small populations [Carpenter (625), Doubleday (1008), Greeley (1549), etc.], or at remote locations [Dye and Mundt (1053), Sharp (3970)].

Hommon (1999) reported that for a waste from 70,000 people with an oxygen consumption value of 86 and suspended solids of 238 mg/l a recommended design would be grit chambers, Imhoff tanks, sprinkling filters, and settling tanks. A bacterial removal efficiency of 82% and a reduction in suspended material from 85 to 3 mg/l were obtained on an Imhoff tank - sprinkling filter plant in California (5076) early in the 1900's. Bacterial investigations by Hotchkiss (2045) indicated chemical and biological activities caused by the film around the stones of a sprinkling filter are similar to those in an Imhoff tank.

Bass (211) reported the rejection of plans to build a direct oxidation plant for Austin, Minnesota, in favor of an Imhoff tank - percolating filter plant to treat the 1.33 mgd at a cost of about $220,000. A description of the Akron, Ohio, treatment plant by Backherms (138) indicated that the Imhoff tanks were designed for a settling time of 2.26 hours at 33 mgd with sludge compartments providing 2.7 ft^3/head and 14 acres of trickling filters (operated at 54 gal./ft^2/day). In evaluating new designs for the expansion of the Akron facility, Kemmler (2426) stated that the combined cost per million gallons of sewage for operation, construction, and interest at 4% over a period of 30 years was $21-$23 for Imhoff tanks - trickling filters, $15-$38 for chemical precipitation, $20-$37 for the activated sludge process, and $30-$46 for intermittent sand filtration, and concluded that the last two are too expensive for consideration for Akron. Data on dissolved oxygen and biochemical oxygen demand of the final effluent of the combined system were reported by Tatlock (4306). Replacement of seepage pits and septic tanks by Imhoff tanks - percolating filter system in Argentina increased the treatment capacity of the daily volume of sewage by 50% (628).

The sewage system to treat a highly acid tomato cannery waste (six-weeks peak load) was described by Hicks (1934) as containing Imhoff tanks and percolating filters (high rate). The BOD loading was estimated to be 510 lb/day, 35% of which was removed by the primary treatment and 55% of the remaining BOD was removed by the percolating filter. An Imhoff tank - biological filtration plant was found to be sufficient to serve a population of 800 at Bristol, South Dakaota (4904), and an additional creamery waste of 5,000 gallons or 68 lb BOD/day, where the total load was not expected to exceed 136 lb BOD/day. Pieczonka (3379) reported in 1956 that an Imhoff tank - percolating filter plant was operated in such a manner that the secondary treatment by biological filtration can be stopped during the winter months. No adverse effects were observed, providing the operation was gradually reduced in late October and early November. The system became operational within three weeks early in May of the following year.

An Imhoff tank - high rate percolating filter plant operating with recirculation was described by Kimball (2481) to handle a designed BOD load of 1440 lb/day, of which no more than 444 lb/day should be contributed by waste waters from the canning of pickled cucumbers. However, these waste waters were found to contain a BOD of 1,277 lb/day, which caused a severe overload; the treatment plant recovered after the passing of these wastes and satisfactory results were obtained. The treatment of a sugar refinery effluent was published by Shukla et al. (4006), using an Imhoff tank - biological filtration plant plus nutrient supplements. A reduction in pollution of the wastes of 70% was obtained, which increased to 92-95% after stabilization of the treated effluent in a tank for 72 hours.

Eddy and others (1093) reported favorable applications of Imhoff tank - trickling filter plants, but could not recommend their use in Chicago, in the 1920's, because of objectionable odors, and substantially the same cost would be involved for an activated-sludge system. Other Imhoff tank - trickling filter plants (5364) which were at the limit of their capacity were modified by building a new Imhoff tank with contact aerators or other aeration devices (4440, 5365). A comparison of the cost of an activated sludge versus on Imhoff tank - sprinkling filter plant resulted in the construction of the activated-sludge plant at Lawton, Oklahoma (5367) in 1929. Hudson (2082) compared the cost of five sewage treatment plants as $28 to $87 per million gallons and $0.83 to $1.70 per head for Imhoff tank - trickling filter plants (Illinois and Ohio), and from $26 to $43 per million gallons and $1.50 to $2.00 per head for activated-sludge plants on an annual basis. After a seriously overloaded condition was reached on the Imhoff tank - trickling filter plant at Rolla, Missouri, a larger trickling filter sewage treatment plant was constructed (4889). Larson (2630) described the modernization of Detroit Lakes, Minnesota, Imhoff tank - trickling filter plant to be: a high capacity Aero-Filter with tile medium; the old Imhoff tank remodeled into a sedimentation tank; the original standard percolating filter, and a final sedimentation tank. Typical of many Imhoff tank - percolating filter plants was that at Marion, Ohio (500). This plant gradually lost its efficiency because of lack of maintenance and normal wear of equipment. The remodeled plant (originally built in 1924) is a combined activated-sludge process - trickling filter plant. Other examples of modernization of Imhoff tank - trickling filter plants were reported by Hagglund and Omachi (1646), Schaetzle (3857), and Cosulich (796).

Critique

Most of the literature dealing with trickling filter-Imhoff tank applications were favorable for the continued use of this means of sewage treatment. The overall plant efficiency may be lower than that of a separate sludge digestion plant, but the low manpower requirements may offset that for certain locations. As noted by several investigators, the economics of the application appear to be the limitation compared to other more rapid systems.

The number of Imhoff tank - trickling filter plants recently constructed is very small compared to those in the 1930's. The system should have an application, with more and more attention being directed toward industrial wastes. The process is claimed to be an adequate industrial waste system requiring minimum operation and equipment. However, the trend was demonstrated that many of the Imhoff tank - trickling filter plants are being converted to more reliable, efficient processes, particularly at municipal treatment plants.

Trickling Filters With Other Methods

Brauss (448) compared the effect of treatment in irrigation fields and in percolating filters. Irrigation fields removed turbidity more completely and reduced bacterial number and coli titer to a greater degree than percolating filters. Marcotte (2860) also compared the treatment of sewage by irrigation, biological filters and activated-sludge process in France. A review by Heidusenka (1856) contains the progress in sewage purification up to 1928, and the comparison of the methods. The Emscher filter was mentioned for the treatment of phenol-containing coke plant waste, provided the effluents are diluted with sufficient domestic sewage. Reich (3532) also reported the use of biological Emscher filters for effluents from coke plants. Kres (2568) stated that phenols from industrial wastes may be destroyed quite readily by biological treatment in Emscher filters or by activated sludge.

The Emscher tank is another concept which has been applied to sewage treatment according to Datesman (874), Schmidt (3875), and Csepai (836). Maier (2835) evaluated several of these combined treatment tanks in 1914, and evaluated their cost versus chemical treatment. Emscher tanks were reported by Datesman (874) to give the best results of clarification and sludge digestion. Scheffel (3859) used Emscher tanks in conjunction with percolating filters. They had 150 cubic meters' (39,600 gal.) settling space with 195 cubic meters' (51,500 gal.) digestion space to treat a sewage flow of 1,500 cubic meters per day (396,000 gal./day). The use of a two-stage Emscher tank in conjunction with a closed aerated trickling filter was reported in 1938 by Sée (3955). Emscher tanks were used at Atlanta, Georgia, (5260), and retained nearly all suspended matter (213 to 303 mg/l). The effluents from the tanks contained 60 to 88 mg/l suspended solids which provided the sprinkling filters in the next stage with excellent operating conditions (5260). Instructions were issued by government agencies, for example the Belgian Ministry of Public and Family Health (5567), on the design and use of septic tanks and small Emscher tanks in conjunction with percolating filters. In 1966, Menkens (2970) discussed the existing theoretical and practical experiences regarding the efficiency of Emscher tanks and percolating filters. Percolating filters were considered superior to activated-sludge plants due to their efficiency and adaptability, and especially their economy. However, large scale sewage works for 30,000 inhabitants and above were more efficient when based on the activated-sludge principle (2970).

An anaerobic process similar to the Emscher tank, which used an anaerobic contact tank, a percolating filter and a small lagoon, was investigated by Fall and Kraus (1237). The process removed 77% of the suspended solids and 34% of the BOD, but the performance of the percolating filter was poor. However, a lagoon was designed which considerably reduced the BOD in the final effluent from this combination plant, which could be safely discharged into the receiving body of water. The "Bio-reduction" process (5318) operated similarly to a pre-aerated settling system followed by percolating filter or other secondary process with charred "bio-loam" being added to the preaeration device.

Critique

Additional multi-unit systems have been used with as many arrangements as there were investigators. Most of these applications were a one-time use for a special problem and would not generally satisfy the requirements of plant design under other conditions. Emscher, Imhoff, Kremer, Stiag and Newstadt tanks have been used with various degrees of success. Most systems that were efficient at capturing solids or could be used for ultimate sludge or effluent disposal have had some application with trickling filters. The usual limitation has been economics and total process efficiency.

MEDIUM SELECTION AND BED DEPTH

Pertinent design factors for the medium of biological trickling filters were given by Bachmann (136) and by "Sewage Treatment Plant Design, No. 36," (4916) for the materials used, size and shape, durability, and placement. The depth of the filter bed medium has received considerable attention and it will be dealt with separately in following paragraphs. Standards, such as the Ten States Standards (5011) and the British Standards (4951), have been established, which outlined requirements for an acceptable medium, such as: the durability of the medium against spalling and flaking; very limited solubility, freedom from iron, structural stability and chemical and biological inertness. Specific sizes and gradings are given, restricting the amount of fine and oversize material. Standards for the use of fabricated media stated that the media be evaluated based on experience with similar waste and loadings before installation. Procedures were specified for delivering and handling the material to guarantee that the underdrains were not damaged and the medium was put in place as designed (5011).

Medium Selection

Requirements of an ideal medium were reported by Pearson (3328) and by Chipperfield (678) as: (a) must offer a surface over which the biological film can grow successfully; (b) the liquid to be purified must flow over the biological film with maximum thickness to assure atmospheric oxygen transfer to the organisms; (c) void space must be adequate for sufficient ventilation to assure aerobic condition; (d) the void space must provide free passage for all organic solids shed (sloughed) from the biological film and be rapidly carried to the next stage of the process; (e) biological inertness must be demonstrated by not being subject to degradation nor inhibiting biological growth; (f) chemical stability must be demonstrated in the presence of dilute quantities of solvents and organic chemicals, etc.; (g) mechanical stability must be demonstrated for long-term compressive stress; and (h) materials should be competitive with any conventional system. A wide variety of media has been proposed for various waste streams, starting conventionally with rock, gravel, coke, peat, then more ingenious uses of coral, empty condensed milk cans, scrap metal, refuse, brush branches, wooden blocks, wooden laths, and, later fabricated elements made of ceramics and clay, cement-fiber, and most recently plastics. These materials of construction are covered in Part II.

In a discussion of the effect of temperature and ventilation on trickling filter operation, Brown (492) emphasized that no general design criteria were fixed for percolating filter media to treat trade waste waters, but that each waste must be considered individually. Smith and Leibee (4074) were of the opinion that the design of a proper medium was important for similar reasons, and stated that it was commercially feasible to produce a better prefabricated medium. Of primary importance from the cost standpoint was the quantity of medium required which was discussed by Temple (4335). Mathematical relations between quantity of medium and efficiency in reduction of BOD have been presented, for example, by Archer and Robinson (85), Germain (1460), Balakrishnan et al. (154), and Roesler and Smith (3658).

Bayley and his coworkers (227) stated that there was some evidence that the size of the filter medium has an effect on the settling properties of the humus generated, such as the larger size medium produced a suspension which was more difficult to settle. The size of the stone was attributed by Montgomery (3076) to be one of the causes of inferior results from high capacity trickling filters. The size of the stone should be from 5 to 7 millimeters (0.20 to 0.27 in.) as reported by Imhoff (2185).

Included in his discussion of the design of percolating filters, Fox (1328) noted the size of the medium and compared his recommended results with those of the Water Pollution Research Laboratory. Watson (4630) reported early in the 1900's that the size of the medium should depend on the character of the waste to be treated and that his experience indicated that the best size was from 0.75 to 1.25 inches in diameter. Easdale (1062) expressed the view that the size of the material for percolating filters should be sufficiently coarse that the humus would be automatically washed out of the filter. The secondary filters used in England (426) contained fine graded medium from 1 to 0.25 inch. The New Jersey State Health Department in 1935 specified that the medium be 1 to 2 inches in size and free from fines (5095). Jenks (2300) stated that the medium size suitable for the biofiltration process should be 1.5 to 2.5 inches for the primary filter and 0.75 to 1.5 inches for the secondary filter. Schreiber stated that a filter bed material 10 to 15 millimeters (0.39 to 0.59 in.) in diameter could be removed and cleaned to eliminate possible clogging problems (3893). The medium proposed by Schreiber (3893) to be used in the "SU" trickling filters was 5 to 10 millimeters (0.20 to 0.39 in.) in diameter compared with 4 to 8 centimeters (1.56 to 3.12 in.) in diameter for ordinary trickling filters.

Meltzer (2965) indicated that maximum efficiency occurred when the optimum rate of flow is used for a specific size and configuration of the medium. A properly shaped medium, which had a large surface area, was stated by Smith and Ellison (4072) to be self-cleaning. However, Schroepfer (3902) contended that the shape has very little effect on filter efficiency. An article entitled, "The Significance of Particle Shape in Relation to Percolating Filter Media," by A. M. Bruce was published in 1968 by the Water Pollution Research Laboratory in the Journal of British Granite and Whinstone Federation (508). Past work on the effect of particle shape was noted, along with information dealing with structural integrity, and it was concluded that elongated particles would provide more void space than equidimensional particles.

Depth of Medium

In the design of biological trickling filters, the volume of material used to support the biological growth was determined by the cross-sectional area and the depth of medium required to produce a desired effluent quality. Easdale (1062) stated that, "within certain limits it is generally found that the same quantity of sewage can be satisfactorily treated per cubic yard of material whether it is in the form of a shallow or deep filter." This is in contrast to Escritt (1204) who said that filters operating by single filtration should be as deep as practicable. A typical example of the procedures used to increase treatment plant efficiency was cited by Molesworth (3055), in which the next phase of experimentation on filters treating effluents from rubber production would be to investigate the efficiency of deeper filters. Another typical example of using deeper filters was given by Fletcher and Anderson (1295), where the existing sewage works at Cumbernauld New Town, England, had its capacity increased by doubling the depth of the trickling filters. Schreiber

(3892) proposed to solve the problems from plugged 6 m (~ 19.7 ft) medium beds by a system in which the medium could be recirculated for cleaning. Several media were developed to achieve a deeper, nonplugging, well ventilated biological filter. Liepolt (2718), Eden et al. (1106), and Chipperfield (681) reported on these fabricated media in which the emphasis was to provide, among other characteristics, a maximum surface area and a maximum void space to facilitate operation of a deeper bed.

All were not convinced, however, that deep bed filters were required, as Reimers et al. (3551) showed that a filter 4 feet deep performed as well as one 6 feet deep. Rudolfs and Peterson (3721) stated in 1926 that filter beds must be at least 6 feet deep to handle 75 mg/l suspended solids. Under the conditions studied, Smith and Rodeberg (4082) concluded that the maximum practical depth of medium was 10 feet, depending on the flow conditions. In a discussion of the differences between low-rate and high-rate percolating filters, Imhoff (2211) described experiments with a filter 8 meters (~ 26 ft) high and one meter (39 in.) in diameter which produced a 90% BOD reduction. However, he advised that it was difficult to construct and that depths of from 3 to 4 m (~ 10 to ~ 13 ft) should not be exceeded, but that instead the filter could be duplicated or effluent recirculated. Keefer and Kratz (2396), in discussing experiments with high-rate trickling filters at Baltimore, found that at a flow rate of 10 mgad (230 gal./ft^2/day) 47.5% BOD reduction occurred through the top 2 feet of the filter, 68% through the top 4 feet, and 80% through the whole depth of 8.5 feet. At a flow rate of 15 mgad (345 gal./ft^2/day), the BOD removal was considerably less. This work was followed much later by Meltzer (2963), who showed that filters 9 and 12 feet deep have little, if any, advantage over 6-foot deep filters.

Much of the confusing design criteria were strongly criticized by Montgomery (3076), in the second of a series of papers clarifying high-capacity and high-rate trickling filters (as previously noted in this review). Part of the cause of inferior results was attributed to injudicious depth of the filter bed. A typical high-capacity filter was that described by Halvorson (1667) to be 8 feet deep and 8 feet in diameter. The shallow, high-rate filter often reported as the Biofiltration process (133, 1286, 1897, 2300, 2303, 2305, 3159) was designed to operate with 3 feet of medium and recirculation. Fischer noted (1284) that increasing the effective depth of the filter above 3 feet had little effect on high organic strength distillery waste. Depth and recirculation were correlated by Rigbi et al. (3612) to show that the size of the filter medium had no effect on efficiency in a recirculating filter 9 feet deep or more. The trend of the depth of medium is shown in Table 2.

Table 2

Depth of Medium Trends

Year	Depth, feet	Reference
1914	8.33	4498
1915	4.6	1089
1919	5.5	3652
1928	7.5	3054
1932	6 - 6.5	1958
1932	8.5	2564
1934	6 - 8	3775
1936	7.5	5485
1936	3	2300
1937	7.5	2108
1945	6.2	5652
1956	30.5	3912
1960	Approx. 30	3329, 681, 3328 1106, 1083

The many applications of trickling filters have dictated varying depths based on design criteria and local conditions. For instance, Furman (1384) reported that percolating filters at a depth of 4 feet were sufficient for the Florida climate instead of the standard 6 feet recommended for colder climates. The New Jersey Health Department established a standard in 1935 which adopted the regulation that filter depths should not be less than 6 feet or greater than 9 feet (5095). Standards have been defined, for example, "Guides for Sewage Works Design," by the New England Interstate Water Pollution Control Commission (5331). The most prominent of the standards often referred to is Ten States Standards (5011), which specify "The filter media shall have a minimum depth of 5 feet above the underdrain and should not exceed 7 feet in depth except where special construction is justified by studies."

The theory behind the relationship of the depth of the filter and the contact time has been discussed previously (Background and Theory of Process). The mathematical descriptions of these relations have appeared frequently in the literature, e.g., Galler and Gotaas (1395), and Robertson et al. (3647). The depth relationship developed by Velz (4535) was later modified by Howland (2064) and Schulze (3915) to expressions relating contact or retention time in the trickling filter to the efficiency of treatment. Levine et al. (2702) reported that the BOD load removal of packing house wastes per unit volume of filter varied directly with the concentration and rate of application of the waste and inversely with the depth of the filter. In studies of air flow and economic design of trickling filters, Pönninger (3410) in 1938 and, much later, Petru (3342) suggested factors such as ratio of the diameter of the filter to the filter depth were significant. Using Velz's (4535) depth formula, Walton (4596) developed a nomograph to aid in the design of a percolating filter which would discharge a final effluent with a BOD of 40 mg/l. A dimensionless factor which related the hydraulic dosing rate, the depth of the filter, and the BOD reaction rate constant was proposed by Gerber (1456). Ingram (2222) suggested that a filter loading ratio, which was the sewage strength expressed in terms of depth of filter, area of filter, volume of sewage, and weight of BOD, would provide a simple basis for calculating filter size. Russian interest in developing a mathematical formula relating the various factors involved in biological filtration and size of filter was expressed by Yakovlev and Galanin (4840) to aid in the design of high-rate percolating filters. Other Slovak efforts in mathematical relations between factors affecting performance of percolating filters have been published by Tucek and Chudoba (4474), in which depth, hydraulic loading, and temperature were related as a primary factor in the design of filters. Eckenfelder (1081) and with Cardenas (1084) proposed relationships based on published and experimental data in terms of hydraulic loading and depth for any specific biological trickling filter medium. Galler and Gotaas (1395, 1397) initially determined depth as an independent variable, and later, during optimization studies, found that depth was dependent on the BOD of the filter influent and the desired BOD reduction, but it was independent of the volumetric rate of the influent.

Critique

After reviewing the literature published on medium selection and bed depth, the extensive information fostered an overwhelming appreciation for the amount of work which the many investigators have performed. From a rather humble beginning of essentially using natural material with a rapid percolation rate placed at a convenient depth to the design and fabrication of specialized media and mathematical expressions relating the depth required to achieve desired removals, the path has been long and tedious. The literature reflected much apparent disparity at first glance. However, it must be borne in mind that a more efficient and economical waste treatment process under specific localized conditions was sought. It is not surprising that at the time Jenks was reporting that 3 feet of rather small rock were required, others were reporting that 6 to 10 feet of a coarse medium were required.

The significant point dealing with medium selection and depth appears to be a complex factor involving an interfacial reaction of the contact time, aerobic biological film, and the waste stream. Whether the contact time was increased by a shallow bed of small material with a controlled recirculation rate, or a deep bed of coarse material with little or no recirculation, was dictated by the economics, the available head, and the existing facilities. The requirements for the medium have been met by several different materials offered over the years. The indications are that with more understanding of the variables involved media will continue to be developed. The mathematical relations dealing with the design of biological trickling filters will be discussed in a later section. However, it has been amply demonstrated in the literature that previous investigators were well aware of the effect of depth and many of the other factors of the medium as they developed their equations and designs.

The economics of a particular situation may advantageously dictate a certain type of material to be used as the medium for biological trickling filtration. As long as the requirements for an ideal medium are satisfied and sufficient experimental evidence of satisfactory operation is available, there is little support to suggest the advantage of one medium over another. Differences in medium will be discussed under the Construction Materials section.

SOLIDS-LIQUID SEPARATION AND RECIRCULATION

Solids-liquid separation and recirculation are both involved in secondary clarification. The solids must be removed from the effluent of the trickling filter. Recirculation of the clarified effluent, the settled sludge plus effluent, and effluent prior to clarification has been practiced in a variety of arrangements. Recirculation and solids-liquid separation are not independent of one another. However, solids may be separated without recirculation, such as primary treatment, and recirculation of nonclarified effluent is an example of recirculation without solids removal.

Separation

Solids-liquid separation was of significance prior to and after biological filtration, as published by Dibdin (946) more than 60 years ago. Primary treatment has been responsible for the removal of the major portion of grit and settleable solids (2984). Dibdin (946) stated in 1910 that the aerobic treatment process on percolating filters provided "the case where sedimentation or filtration is required to collect the humus discharged from the percolating beds." This was secondary clarification. Dahlem (853) concluded much later that high-capacity trickling filter units required good subsequent clarification of the sewage. Hurley (2121) cautioned that the selection and design of humus tanks following percolating filters and sludge removal were important. Typical of the many systems proposed was that of Hall (1652) who described a tangential inlet sedimentation tank.

Factors affecting the sedimentation of humus and effluents from percolating filters were investigated by Bayley and coworkers (227). They determined that it was possible to predict the effects on sedimentation due to the initial concentration of suspended matter, the depth of the suspension, temperature, and the degree of purification achieved by the trickling filter. Unfortunately, no accurate method was found for predicting the performance of humus tanks from their design and operating conditions. For the purposes of design, under quiescent settling conditions, no significant improvement was obtained by introducing transverse baffles at the inlet, by reducing the width of the tank, or by installing longitudinal baffles in very wide tanks. The fundamental factors were considered by Eliassen (1150) to be the detention period in the settling tank and the rate of overflow of the clarified waste at the weirs. Whitehead (4713), in a written discussion of the paper by Escritt, stated that 200 gal./ft^2/day of dry weather flow should be provided for both upward-flow and horizontal-flow tanks.

The approach of Berry (296) to achieve better solids capture was to use upward-flow clarification in a Dortmund-type tank and automatic sludge removal. Upward flow sedimentation has been used ahead of trickling filter waste treatment by Sviridov (4271), as well as by Watson (4630) in post-trickling filter applications. Watson reported in the early 1900's that the best sedimentation was obtained with an upward flow of about 21 ft/hour. A sludge-blanket principle was successfully used by Barnard (180).

Mechanical filtration by various sand filters to achieve solids capture has been described in several treatises (2984, 4916). Detailed design and operations information for the mechanical filtration of sewage and sewage sludge with several types of filter medium was dealt with by Dickey (957) in his book. Typical of the many patents issued on various mechanical filtration schemes was that to von Roll (3678) and others (4098), covering various processes of cleaning the medium.

Centrifugation has been considered off and on since the 1920's, as noted by Fuller (1376). In attacking the conditions of many wasted acres of sewage farms around Berlin, Böttcher (418) suggested that centrifugation should be considered for sludge dewatering and drying. He also mentioned that the agricultural value of sewage is greater after mechanical treatment than after biological treatment, which favored centrifugation. More recently, Ingram and Edwards (2225) successfully applied centrifugation prior to the waste being applied to air-gapped trickling filter medium. Centrifuging of the settled sewage before the filter reduced the BOD to about 67% of the total BOD, and the filter then removed 63% compared with 53% for mixed settled sewage. The overall removal of BOD from settled sewage by centrifuging and filtration was 75%. Few suspended solids remained after filtration. An objection was raised by Garrison and Geppart (1417) who used several different processes to remove suspended material, such as greases from packing house waste. Their results indicated that the high capital investment and operating costs ruled out centrifugation.

Solids-liquid separation has been reported so extensively that a comprehensive coverage of the subject is beyond the scope of this review. Of the several unit operations used in waste water treatment, sedimentation, mechanical filtration and centrifugation, as well as flotation, are among those which are best understood. L. G. Rich (3586) and Babbitt and Bauman (112) have written textbooks relative to sewage sedimentation with references to the original sources.

Recirculation

Recirculation is a common technique to control the efficiency of biological trickling filters. Recirculation on standard and high-rate trickling filters was shown by Hansen (1719) to have certain advantages, but economic questions have been raised. By the end of World War II, according to Hurley (2121), recirculation of the effluent from percolating filters was widely used in this country. Various schemes of recirculation on single and two-stage trickling filters are illustrated in Figures 4, 5, and 6. The flexible operation of the recirculating system on trickling filters to obtain uniform quality of effluent established its wide-spread use, as described by Eliassen (1151). A system could then accommodate the varying requirements of Army camps in the United States. Fowler (1326) discussed the revival of the percolating filter concept based on recirculation.

In the operation of a Biofiltration plant, Verna (4538) pointed out the significance of the ratio of the recirculated effluent to the settled sewage influent. Imhoff (2205) reported on investigations which demonstrated the advantage of a constant rate of flow of sewage, which could be kept by recirculating part of the filter effluent. Recirculating trickling filters were simpler to operate than enclosed aerated filters. Similar comments were made by Escritt (1199) on the design

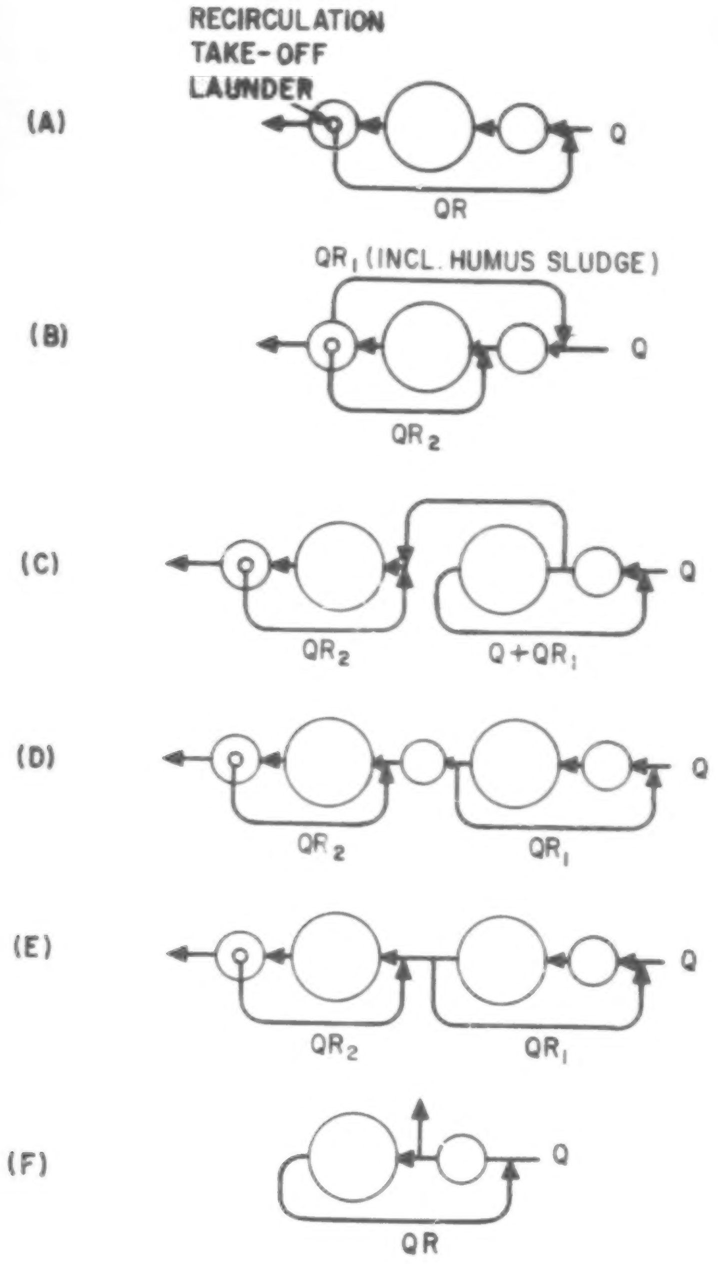

RECIRCULATION TAKE-OFF LAUNDER
(A)
Q
QR
QR₁ (INCL. HUMUS SLUDGE)
(B)
Q
QR₂
(C)
Q
QR₂
Q+QR₁
(D)
Q
QR₂
QR₁
(E)
Q
QR₂
QR₁
(F)
Q
QR

Fig. 4 - Biofiltration Recirculation Diagrams

Typical Biofiltration Flowsheets. (A) and (B) are single stage; (C) is two-stage with progressive feed; (D) and (E) are two-stage, and (F) is single stage, intermediate. Sludge lines are not shown except as noted in (B). In all flowsheets humus sludge from the final clarifiers and intermediate clarifier is returned to the influent line of the primary clarification tank.

[by Permission of Public Works Journal, "Handbook of Trickling Filter Design" (5574, p. 19)]

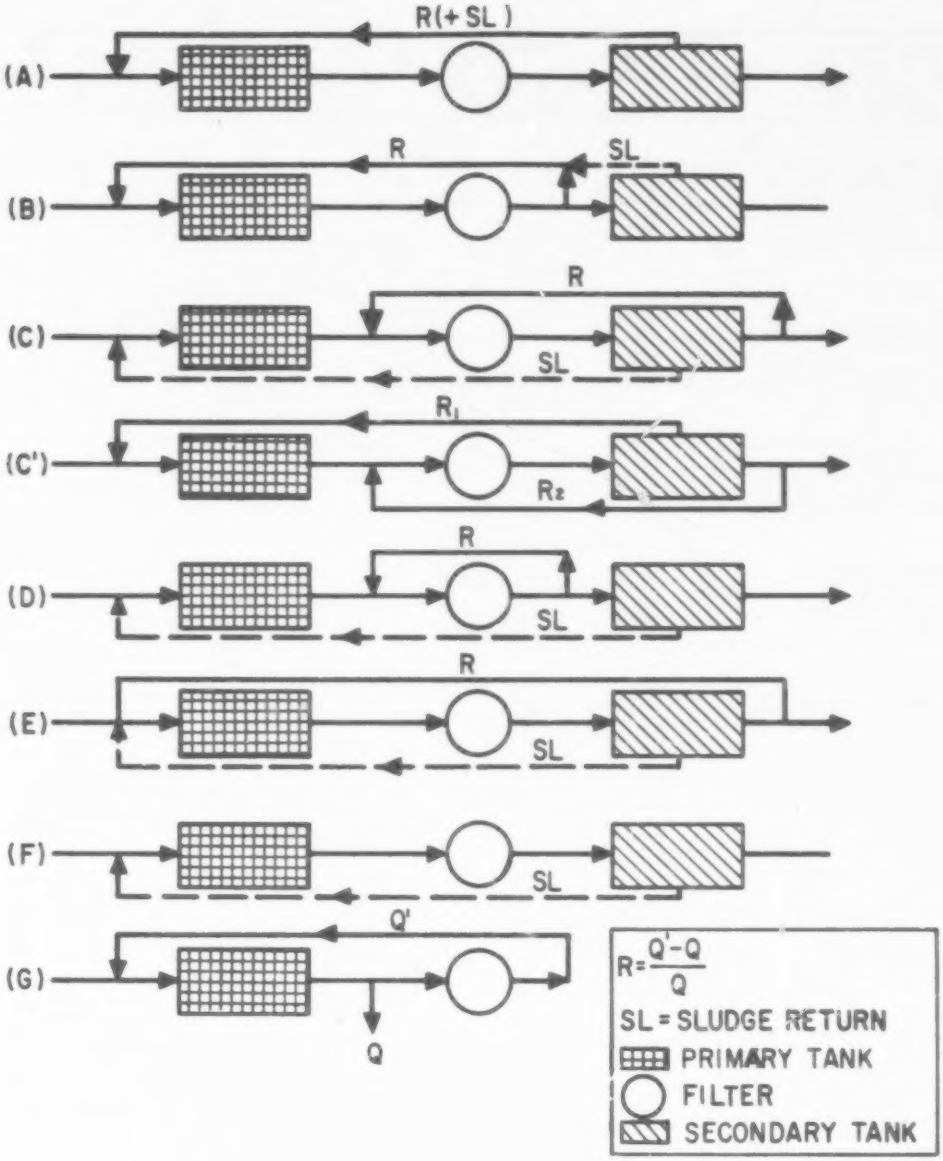

R(+SL)
(A)
R
SL
(B)
R
(C)
SL
R_1
(C')
R_2
R
(D)
SL
R
(E)
SL
(F)
SL
Q'
(G)
Q
R = (Q' - Q)/Q
SL = SLUDGE RETURN
PRIMARY TANK
FILTER
SECONDARY TANK

Fig. 5 - Flow Diagrams of Single Stage High-Rate Filtration [by Permission of American Society of Civil Engineers (4916, p. 157)]

Flow diagram (A) - the secondary sludge is returned to the primary tank and, other than (G), all systems required separate pumping arrangements for secondary sludge removal. Flow diagrams (A), (B), (C), (E), and (G) dampened fluctuations in the organic loading applied to the filter. Flow diagram (D) recycled filter sloughings to the filter. All flow diagrams, except (D) and (F), required consideration of the recirculated flow from which (E) was usually considered uneconomical. Flow diagrams (F) and (G) were used for partial treatment. Flow diagram (C') included the recirculation features of (A) and (B).

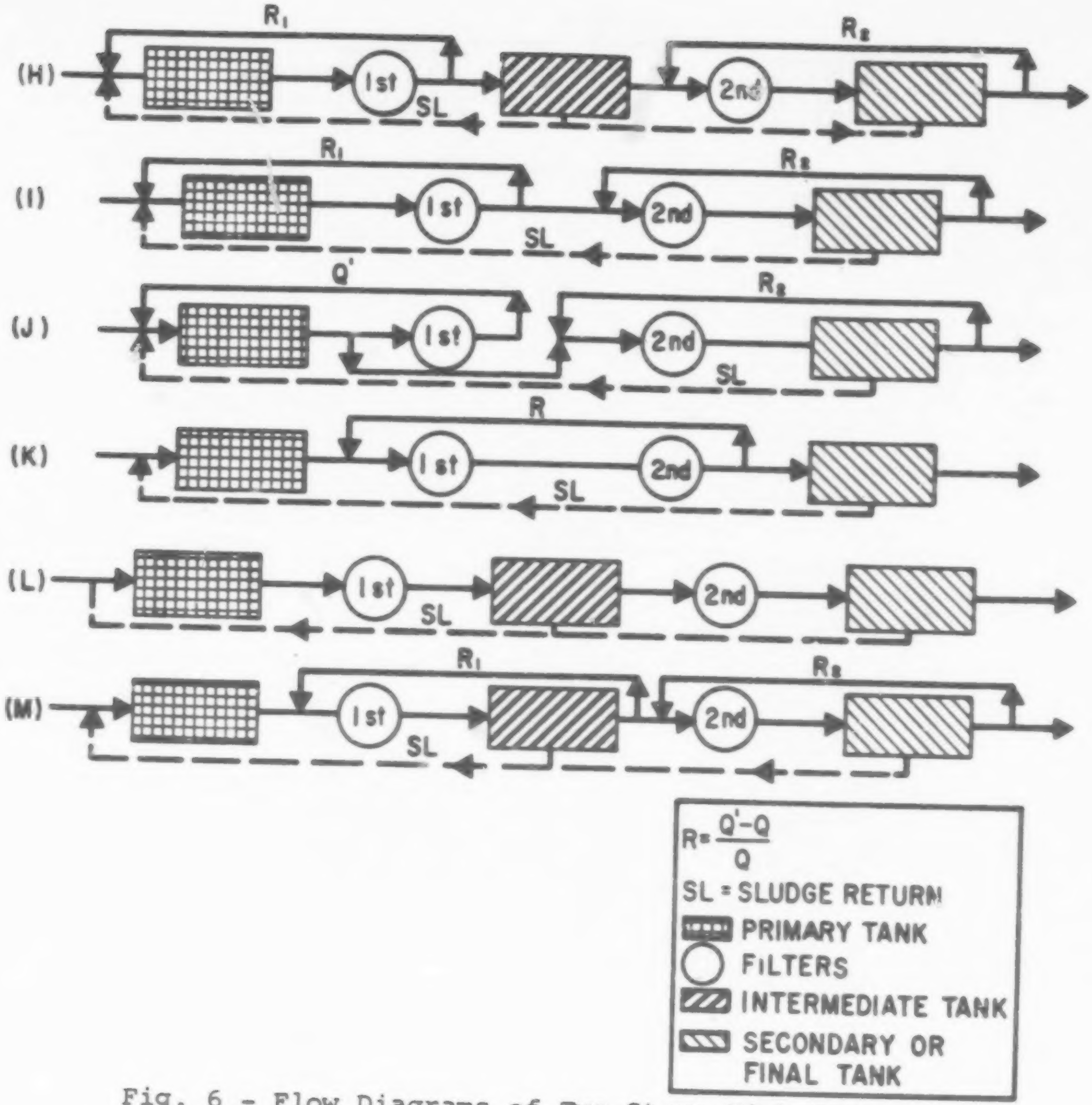

(H)
(I)
(J)
(K)
(L)
(M)
R₁
R₂
R
Q'
1st
2nd
SL
R = (Q'-Q)/Q
SL = SLUDGE RETURN
PRIMARY TANK
FILTERS
INTERMEDIATE TANK
SECONDARY OR FINAL TANK

Fig. 6 - Flow Diagrams of Two-Stage High-Rate Filtration [by Permission of American Society of Civil Engineers (4916, p. 158)]

Flow diagrams (H), (I), (J), and (M) have been used most frequently. Flow diagrams (H), (L), and (M) could be utilized as low-rate filters for the second-stage unit. Flow diagrams (I), (J), and (K), in addition to eliminating the intermediate settling tank, were attempts to improve treatment by developing greater biological activity on the second-stage filter. In flow diagram (J) a part of the primary settling-tank effluent was by-passed directly to the second-stage filter; in flow diagram (I) a part of the settleable sloughings from the first filter effluent was applied directly to the second filter and the recirculated flow was not settled.

of recirculating trickling filters in England. Recirculation relative to the efficiency of percolating filters was discussed by Lumb (2781) in a symposium on the treatment of waste waters. Typical of recirculation ratios used by Fischer (1285) in the biofiltration system were:

(a) 2:1, producing a reduction in BOD of from 50 to 60%.

(b) 1.5:1, producing a BOD reduction of 75 to 85%.

(c) 1:1, producing a BOD reduction of 90 to 95%.

Meltzer (2964) stated that a recirculation ratio of 1:1 will give an increase in detention period of 19% while 2:1 recirculation will increase the detention period by 30%. Archer and Robinson (85) found that recirculation improved overall efficiency of the plant and that a recirculation ratio of 4:1 can reduce the required volume of medium. Dreier (1029) in 1947 maintained the flow rate to the filters at a 1:1 ratio with recirculation ratio at average flow.

Meltzer (2965) pointed out, however, that effluent recirculation appeared to have no theoretical advantage over filtration in deep filters from the efficiency standpoint. Imhoff (2185) found that stronger sewages required either deeper filters or recirculation of the effluent to achieve a desired removal. It was noted by Rigbi et al. (3612) that, when the rate of recirculation produced the effect of a filter 9 feet deep or more, the size of the filter medium had no effect on the efficiency. Escritt (1204) used recirculation instead of a deeper filter, and suggested that the depth of the filter multiplied by the recirculation ratio plus one should equal the depth of a single filter.

Imhoff and Dahlem (2204) suggested that single filtration operating at a low rate of flow is the simplest form of filtration, but has disadvantages of odors and nuisance from flies; however, with filtration at a high rate and recirculation of the effluent, these were reduced. The obvious disadvantage of recirculation is the cost of pumping the sewage; however, the filter area is less and the recirculation can be controlled automatically. Recirculation is one of four ideas to reduce blockage caused by excess amounts of organic matter, as cited by Watson (4640).

Typical of reports published on the operation of percolating filters with and without recirculation were those by Yakovlev and Galanin (4840), Ziegler (4863), Benzie and coworkers (273), and Greeley (1564), and Greeley et al. (1566). Additional papers by Hurley (2118) and others (4940) compared recirculation with the alternating double filtration technique. Recirculation has been used to increase the efficiency of plants in England (2879), Israel (3612), Germany (3785), and

India (3055). Recirculation on many industrial wastes has been reported by Hatfield (1792) and by Kirchoffer (2494) to such an extent that they will be reviewed in the sections of the specific industrial waste streams in Part IV.

Recirculation involves the collection of the waste water at some point in the process and transporting it to another point. Examples of different schemes of recirculation are illustrated in Figures 4, 5, and 6. Recirculation of the trickling filter effluent directly without any clarification has often been used by Bachmann(133) in the Biofiltration system. Direct recirculation of strong, fine-chemical plant waste was part of a system reported (3551) to produce 80% BOD removal. Typical of many of the patented systems was that issued to Gillard (1474), in which the operation of the Accelo-Filter depended on the direct recirculation of unsettled filter effluent to the stream of settled sewage being applied to the filter. With the development of the package plant concept, as exemplified by Knapp et al. (2514), recirculation played a vital role. At Suffern, New York, recirculation of primary filter effluent was an integral part of plant expansion in 1960 (5411).

Bartlett (205) in 1954 stated that it was desirable to design trickling filter plants with recirculation of filter and/or humus tank effluent. Operational experiences reported as far back as 1938 by Herrick (1897) suggested the use of recirculation of effluent from other unit operations, such as Imhoff tanks, to stabilize the biological growth in percolating filters. A practice in the redesign of percolating filter plants in England was to operate with recirculation of the effluent of all units of the system up to and including the trickling filters (3383). In the design of secondary treatment plants, the practice was to provide recirculation of the secondary sludge to the primary sedimentation tanks (4905).

Another scheme of recirculation used by Sickert (4013) was the two-stage operation of a trickling filter activated - sludge plant in which one bay of the activated-sludge plant was used for reactivation of recirculated sludge. Other designs which used direct recirculation of percolating filter effluent were reported by Theinpont (4352) and Borden (409). Monson (3068) recirculated a milk trade and domestic waste influent, and Bergman (277) described a recent plant expansion using direct recirculation for three townships in Orange Free State, South Africa. Ouellette (3260) at Elizabethtown, Kentucky, and others (5046) in France, and Greaves (5533) and Calvert (593) in England used direct recirculation. Herriot (1899) outlined some engineering points dealing with recirculation and alternating double filtration including economics. Clarified effluent was frequently recirculated, as was mentioned by Guerrée (1614), Lugt (2777), Griffin (1593), Fletcher and Anderson (1295), Weller (4673), and Banister and Ellison (162).

Several design factors of recirculation in conjunction with trickling filter operations were reported in the literature. Climatic effects and loading factors were discussed by Benzie and coworkers (273), where recirculation through the filter had a marked cooling effect during the winter and lowered the efficiency of summer operations by 21%. Smith (4060) reported recirculation rates in terms of pounds of BOD/ac-f/day. A single stage filter operated with recirculation of 1,000 to 2,000 pounds on an influent of 350 to 400 pounds of BOD/ac-f/day (8 to 9 lb of BOD/1,000 ft^3/day).

Recirculation of sewage gave a washing effect, as noted by Imhoff (2182), and had to be done at a velocity of sewage sufficient to keep the filter from plugging. Reimers et al. (3551) experienced the tendency of ponding, which was minimized by increasing the recirculation rate, supporting the concept of Imhoff (2182) some 17 years earlier. Several papers, e.g., Sharp (3970), Eliassen (1154), and Smith (4060), have been published specifying factors of design for recirculation. Recirculation was used as an acclimatization procedure by Oeming (3216) and Tedeschi and Lucas (4330), who reported that stage operation at varying recirculation rates resulted in a stable effluent.

Much of the data gathered and compiled by the Great Lakes-Upper Mississippi River Boards of State Sanitary Engineers was statistically correlated by Fairall (1233). The performance of trickling filters with and without recirculation was compared to that predicted from the Ten State curve. The best correlation was obtained for first-stage filters with recirculation. Galler and Gotaas (1395, 1397) considered recirculation as one of five independent variables in their data analysis. Increasing the recirculation ratio was advantageous until the ratio reaches four volumes recirculated liquid to one of the plant influent. The Biofiltration process which incorporated a high degree of recirculation was reported by Jenks (2305) to have its capacity decreased once the ratio of recirculation to rate of flow exceeded six. The practical upper limit for domestic sewage was found to be 120 mgad (2,760 gal./ft^2/day). Fischer and Thompson (1279) and Fischer (1284) described the effectiveness of the Biofiltration process of single-stage and two-stage at low recirculation ratios and noted that the dosing rate on the filter should not fall below 4 to 8 mgad (92 to 184 gal./ft^2/day) or should not exceed 100 to 125 mgad (2,300 to 2,875 gal./ft^2/day).

High recirculation processes require land area slightly greater than activated sludge, but less than one-quarter that for a trickling filter, according to Jenks (2305).

Montgomery (3074), in a discussion of poor operation of Aerofilters, stated that it could be due to inadequate recirculation, among other things. Economic preference was given to two-stage filtration over single-stage filtration with parallel recirculation. Galler and Gotaas (1397) later related the cost of recirculation rate, filter size, and filter diameter.

Critique

It would appear conservative to say that the solids-liquid design technology has been worked on to the extent that meaningful criteria are established. Techniques such as polyelectrolyte treatment to aid the separation are not covered. However, for design purposes, chemical addition would only change the detention time required for a given clarity or effluent quality for the same detention time. The design must still have a facility for collection, separation and transport to the next process step, as was reported by most workers. Until power costs become extremely reasonable, or the price of land too high, centrifugation and other energy-consuming systems may be reserved for specialized applications.

The literature on recirculation was typical of that encountered in other areas of this review. Most of the designs for new plants were reported after the fact, and each installation was improved over the last ones, producing a confusing picture. This confusion was noted by authorities, such as the American Society of Civil Engineers, which only have examples of the practiced art and not the correct designs, as shown in Figures 5 and 6. Work has been done, as reviewed in the theory section, but much of its practical application is for future work. Generally, it can be said that recirculation does help plant operation, but not necessarily efficiency, and that an upper limit is four to six volumes of recycle to one volume of influent. Those in the field, not mathematically inclined, should be enlightened by some of the reasoning used in recirculation design. Furthermore, a set of operation criteria could be established based on past experience and problems. These criteria, if properly prepared, could be used by operators and designers to handle specific waste treatment problems. With knowledge of previous experience available, some of the unsupported design and poor operation may be lessened.

EFFECT OF PRETREATMENT

"Pretreatment" describes those unit operations beginning at the influent pipe of the plant up to and including primary sedimentation. Economic factors have caused investigators and operators to study the effect of these pretreatment units on subsequent treatment processes.

Reid (3548), a Scottish investigator, has outlined designs for typical sewage works for small villages, such as percolating filter plants built without screen or detritus channels, to lower the cost of maintenance labor for isolated installations which have little chance for inspection. Rumpf (3782) reviewed the work of Tomlinson and Hall (4425) on the operation of percolating filters with and without primary sedimentation during the development of the alternating filtration system. From some of Hall's work (1653), it was concluded that the degree of purification in the trickling filter does not bear a direct linear relation to the strength of the tank effluent applied to it. Hall did note that improved sedimentation was capable of giving higher filter loadings by 15 to 20%.

A patent was issued to Jung (2354) for a process in which raw sewage without sedimentation was applied directly to a percolating filter. Osborn (3251) found that the absence of primary humus tanks resulted in an increase in the suspended solids in the secondary filter effluent, but did not reduce the quality of the final effluent during double filtration operations. These results were in fair agreement with those of the Water Pollution Research Board (5193), which noted the presence of the clarifier was not proven essential. The Water Pollution Research Board was primarily interested in the effect of secondary treatment with little or no pretreatment based on two developments (5193). These developments were: "first, the commercial introduction of small maceraters, and secondly the development of plastic filter media which were not so readily blocked as conventional media."

Most of the designs were to condition wastes for subsequent treatment, as Lawton (2648) reported. Where the suspended solids were reduced to less than 100 mg/l, as would be the case with chemical precipitation, then a fine filtering medium 0.125 to 0.375-inch diameter was preferable.

The detention period in primary sedimentation in the early 1900's was recommended by Ogden to be about two hours (3220). A common pretreatment technique in the early 1900's was the use of a septic tank dosing chamber, in which an average detention period of 4.5 hours removed 72% of the suspended organic matter, according to Doten (1005). Prior to 1940, pre- and final sedimentation of 1.5 to 2 hours was specified by Imhoff (2185) to be necessary for proper waste treatment operation. Rankin and coworkers (3501) described in considerable detail the type of treatment required before biological filtration.

Typical designs of the 1930's cited by Hughes (2084) included coarse screens, detritus tanks, fine screens, and continuous flow sedimentation tanks. A plant flow sheet in 1931 (2069) included a screening process, an automatically cleaned screen system, a grit scrubber, and mechanically cleaned settling tanks, which was not too different from the type of plant described in 1956 by Stuewer (4261). In addition to the preliminary facilities noted, chlorination was used (4673) in handling septic waste. Another pretreatment approach described by Barron and Lawrence (199) was raw sewage chlorination for odor and nuisance control. The application of chemicals to aid sedimentation at a recent sewage plant development was noted by Greeley (1557). Preflocculation without chemicals to aid solids capture was discussed by Fischer and Hillman (1282).

Preaeration to raise the dissolved oxygen in a septic or very strong waste was reported by Collom (763), Holland (1979), Vogler (4545), Anderson (77), and Thomson (4380). Dreir (1029) noted that preaeration, either mechanical or by diffused air, for 30 to 40 minutes, at a maximum hourly flow, satisfactorily removed grease and increased primary sedimentation efficiency as measured by primary BOD removal. He also suggested that by increasing the primary sedimentation efficiency operational advantages could be gained. Higher dissolved oxygen in the waste, toleration of a much higher organic load, and withstanding the introduction of the supernatant into the flow were among the benefits of this technique. Nauta (3150) stated that with continuous short aeration periods 70% purification could be obtained, and the aerated sewage could be treated on percolating filters at increased rates. Ingram (2224) agreed that with suitable preliminary treatment of the waste water, which involved pH manipulation and suspended solids removal, a higher rate of controlled filtration was feasible.

Pretreatment in industrial applications was common in processing potato waste waters, such as screening, disintegration, sedimentation, and flotation (5330). Vogler et al. Hendee (4545) stated that strong pharmaceutical and organic chemical wastes can be treated by biological filtration but preliminary treatment, similar to that outlined by Reimers et al. (3551), is often necessary. Genetelli and coworkers (1452) indicated that minimal (70% BOD removal) preliminary treatment was necessary before discharging pharmaceutical waste into a domestic sewer system. Pretreatment of this type would require a more sophisticated plant than was suggested by Snyder (4094) which consisted of an equalization pond and a final sedimentation tank to handle a variable flow textile waste. Other industrial wastes, such as milk processing waste as recorded by Kirchoffer (2494) and Salvato and Bogedain (3814), required preliminary treatment to handle high organic and suspended solids loads. For turnpike sewage treatment plants, Dixon and Kaufman (977) recommended anaerobic treatment in advance of biological filtration to solubilize greases and colloidal suspensions from detergent emulsification. Antipina (83) recommended that the waste waters from ethylene oxide production should be pretreated by a 4:1 dilution with domestic sewage. The dilution of industrial sewage with domestic sewage is common practice.

Critique

Pretreatment of the influent by mechanical and chemical means has improved the efficiency, operation and maintenance of trickling filters. Studies were also made on the partially successful operation of trickling filters with no pretreatment, other than a bar rack. However, to deviate from established practice, special design must be considered or new operational problems must be expected. An example would be a trickling filter plant designed without a primary clarifier. If the medium was coarse enough and the distributor and underdrains sized properly, this system should perform adequately. On the other hand, if a low-rate plant is operated without the primary sedimentation tank, there should be no surprise when operational problems arise.

Chemicals for pretreatment have been applied for many years and will probably continue for many more. Nuisance control, solids capture, pH adjustment, and nutrient supplements are just a few of the methods of pretreatment of sewage.

Additional information of unit operations and their relative performance with pretreatment would be of value using newly developed instrumentation. Use of chlorine for pretreatment is covered more deeply under maintenance of trickling filters.

EFFECT OF POST-TREATMENT

The necessity for post-treatment of effluent from biological filtration was recognized as necessary very early and became commonplace. Lawton (2648) observed that to obtain a good effluent it is essential to remove suspended solids which are carried from the filter. In the early 1900's, Ogden (3220) stated that a two-hour retention period was used for humus tanks (clarifiers) to retain the particles in suspension, thereby clarifying the effluent. Information dealing with the design, construction, and operation has been published in a series of papers in the Public Works Magazine (3501, 5378, 5574), which illustrate the importance of the post-treatment of filter effluent. Typical of many design papers was that of Borden (409), which indicated that the biological filtration process is integrally related to the final sedimentation process. Hottelet (2048) stressed the importance of secondary sedimentation when using biological filtration.

During the development and testing of the Biofiltration process, Fischer (1286) and Fischer and Thompson (1279) stressed the significance of post-treatment clarification with careful monitoring of suspended solids. Installations at Sullivan County, New York, were reported by Borden and Rodie (410), Rochdale, Lancaster, England (5218), Hayton-with-Roby in England by Pilkington (3383) and on the New York Thruway by Sander (3818) to be typical in using post-treatment procedures on percolating filter effluents. Data gathered by Rigbi and coworkers (3612) under field conditions indicated the difference in efficiency with and without post-treatment sedimentation and secondary sedimentation was favored due to the 10% increase in BOD removed. The significance of final removal of suspended solids and its effect on the treatment of trade waste waters were discussed by Escritt (1205). Reimers et al. (3551) noted that secondary or final clarification was necessary for the discharging effluent and not for the recirculated portion of a pharmaceutical waste.

Sand filters, described by Streander (4244) as being composed of 28 inches of sand and 4 inches of gravel, were used for post-treatment for many years. Microstrainers as a tertiary treatment were studied by Fish (1290), Keefer (2406), Truesdale et al. (4468), Roberts and Lawson (3637) and Colthrop Board and Paper Mills (4963), and incorporated for successful solids removal. Disinfection with chlorine was stated by Newton (3179), Brown (490), Lafontaine and Armstrong (2607) and Rofman (3660) as a common practice of post-treatment.

Critique

Pretreatment and post-treatment of biological filtration were reviewed to provide the identification of distinct areas apart from the trickling filter which have very strong bearing on its performance. It is well agreed that solids separation after filtration is important. However, the investment for secondary clarifiers may not be justified. If only 10% increase in BOD removal is obtained by an expensive appurtenance such as a sludge scraping settling tank, then, perhaps another method should be sought or the money not spent. The weakness here is using the BOD test to measure effluent quality and an implied BOD removal due to solids capture. The BOD test was designed for a specific purpose, to assess the stability of an effluent in a receiving stream, and not to measure the effectiveness of secondary clarifiers. The polluting powers of the suspended materials would have to be evaluated in a manner other than the dilution BOD test.

Disinfection of the final effluent before release from the sewage plant is a common practice and would justify a separate review. Microscreens for filtering solids have been used, but screen plugging on secondary sludge is to be expected.

SOLIDS DISPOSAL

A function of the biological trickling filter plant is the coagulation of colloidal particles and removal of soluble organics which generate a sludge disposal problem. Various designs have been proposed by Dreier (1028) and Eckenfelder and O'Connor (1080) for sludge disposal. A comprehensive review of sludge handling techniques has been prepared by Burd (533), and detailed discussions of these methods are beyond the scope of this review. Selected techniques are briefly mentioned to demonstrate an awareness of the sludge disposal problem.

Imhoff (2197) stated, in 1941, that fresh, fully digested and dried sludges are odorless. Very offensive odors are produced in the intermediate stages; therefore, nothing but digested sludge should reach the drying beds. If it is necessary to dry fresh sludge, more rapid methods of dewatering were recommended. Geographical location was stressed by Furman (1384) as significant for sludge drying, i.e., southern climates require less area. Sludge drying beds were used and the dried sludge stored or delivered to farmers, according to Burger (535). Occasionally, unique geographical situations were used, as noted by Collom (763) in Auckland, New Zealand, where a volcano crater was used as a sludge lagoon following anaerobic digestion.

Easdale (1064) described a technique which was a forerunner of the Imhoff tank, except that decomposed solids were intentionally allowed to pass out with the effluent to primary contact beds or percolating filters. The importance of sludge recirculation was often noted by investigators such as Fowler (1326) in 1938 and Condon (766) in 1966. Widespread use of Imhoff tanks in conjunction with trickling filters to handle sludge digestion was described by various investigators, e.g., Burger (535), Kuhn (2586), and Richey (3592).

A very popular method of reducing sludge volume and putrescibility during the 1930's, '40's, and part of the '50's was sludge digestion under aerobic conditions, as described by

Allen (35). Greaves (5533) reported sludge from primary sedimentation tanks was concentrated, digested, and dried on beds, and the sludge from the final sedimentation tanks was recirculated to the head of the plant. Heated and unheated sludge digestion was cited by McIntosh (2914), Storrie (4237), Phillips (3369), Ellsworth (1162), Heaton (1846), and Veatch (4524), with the digested sludge being discharged to open or glass-covered drying beds.

Sludge presses were used (1846) to dry the sludge more rapidly. Sludge which was treated with lime and pressed was commonly used as fertilizer by farmers in Great Britain. Watson (4712), as a proponent for sludge disposal on land, emphasized that sludge from sewage works preserved most of the mineral constituents of sewage in a form more readily available as fertilizer than when the sewage was applied directly to the land. Primary sludge has often been deposited in lagoons, while secondary sludge was spread over land (5464). Reimers et al. said that sludge from a pharmaceutical waste treatment plant could be satisfactorily spread on land for disposal (3551). A common technique used today is chemical dewatering on vacuum filters and incineration of the dried sludge (766).

Critique

Other than to note that the investigators and workers in the field of trickling filter design were cognizant of the problems, discussion of sludge disposal will be minimized. Efforts were made wherever possible to eliminate the sludge from the receiving body of water. The methods of sludge disposal were so varied that it took a sizable volume to contain a recent review of them. Simply stated, it was noted by Sir Lawrence Chadwick of the British Royal Sewage Commission, prior to the turn of the century, that the disposal of solids to the land and sewage to the river should provide the solution for waste disposal. However, he was of the opinion that "the solution to pollution is dilution." This opinion has since been proven slightly shortsighted, as shown by the rise of secondary waste treatment facilities, such as percolating filters. However, his comments dealing with the disposal of solids on land still have current practical and economic significance.

EFFLUENT DISPOSAL

In complete waste water treatment, the job is not finished until the effluent from the sewage treatment plant has been released to the receiving body of water and is harmless to the environment. The state and condition of the effluent are quite important to its receiving body of water, as expressed by many investigators. Concern was expressed by

Shaw (3975) over the effluent standards that have been legislated and observed early in the literature by many investigators, such as Donaldson et al. (995) and Rohde (3666). Fuller (1369) cited six types of conditions of stream flow which should dictate the type of treatment required. He strongly emphasized that a uniform degree of purification in all situations was not practical. According to a survey by Thompson (4371) covering 25 years, the developments in methods of sewage treatment since 1910 can be attributed to the work of the Royal Commission on Sewage Disposal, and later of others, such as Mulvany (3121). These investigations evaluated efficient methods of sewage disposal to reduce the pollution of streams, as well as set up monitoring procedures for various pollution control agencies. A classic example of this type of effort was the investigations by Biery (325) on the Ohio River system which were carried on for some 25 years to develop local, regional, and federal legislation to establish effluent disposal requirements. Typical of state activities was that described by Poole (3424), in which the Indiana Stream Pollution Control Board developed criteria which would avoid gross pollution of streams during periods of low flow.

During the design of a waste treatment facility and before selecting a specific process, engineers, such as McKinney (2925) and Smith and Leibee (4075), have often stressed the importance of evaluating the characteristics of a waste water and the effluent standards in the local area, and the need for preliminary treatment. It was pointed out by Phelps (3360) that early investigations to demonstrate the effectiveness of waste treatment were done by the Pasteur Institute to establish effluent disposal which would reduce gross pollution of the streams in northern France. Weber stated (4654) that the effluent quality of the sewage treatment plant was established after an examination of the receiving stream, the Enz in Germany, which dictated the degree of purification (80-85% BOD removal) the plant must achieve at Pforzheim.

Typical procedures involving effluent disposal design for the process of upgrading waste water treatment have been described. Irwin and French (2235) stated that primary treatment alone resulted in producing an effluent which affected the receiving stream by the development of a heavy growth of fungi and a reduction in the dissolved oxygen content as well as an increase in the BOD of the river water. Ammon (69) determined the initial condition of streams receiving milk processing waste waters and the corrective treatment was specified. Mills and Wheatland (3017) discussed the treatment of high salt concentrations which make the effluent unsuitable for irrigation or for a public water supply. Boone (403), Tiedeman (4392), and Rowe (3700) modified the typical overloaded plant to chlorinate the effluent, which was finally discharged to a small creek to prevent disease or nuisance problems.

Effluent quality becomes very important in areas of scarce potable water, which has developed a growing demand for effluent reuse. In 1931, German investigators (5614) noted that biological treatment is necessary when a stream affords less than a 50:1 to 100:1 dilution of the waste and is used for bathing or washing beyond the point of discharge. Effluent must be of high quality when it is discharged to a body of water that is used as a potable water supply, as reported by Majewski (2842), Saunders (3831), and McPhee and Smith (2941). In Pennsylvania, the city of Bethlehem was very much interested in the treatment which Allentown provided to their sewage because it was discharged to the Lehigh River, and four miles downstream it was the source of Bethlehem's water supply, according to Krum (2575). Very high degrees of treatment have been accomplished over the years for municipal waste (Yonkers and Fairfax) as well as industrial waste in areas where the water was to be used as a potable water supply (3831, 5138). It was pointed out by Shastin (3973) that effluents of a rosin plant in Russia have been purified to a high degree (90-95%) and were discharged, without problems, to a small river. Ground water recharge was practiced on Long Island as cited by Baffa and Bartillucci (431). Another use of the effluent, depending on its quality, was studied by Minett et al. (3027), who supplied this effluent to cattle. The symptoms shown by cattle in cases of alleged sewage poisoning were attributed to other causes.

The very old procedure of irrigation as a final step in wastewater treatment was described by Fidler (1260). The rates of application were around 8,000 gal./acre/day (0.184 gal./ft^2/day) on a 495-acre farm, while even a low-rate standard design trickling filter was designed to operate at 3,600,000 gal./acre/day (82.8 gal./ft^2/day), according to Galligan (1399). In studies in Germany by Brauss (448) on the use of sewage effluent as a water supply, it was noted that the bacterial numbers introduced into a stream by filter effluent are about the same as those introduced from sewage irrigation fields. Popkin and Bendixen (3430) studied the relationship of proper irrigation rates for various soils. Girard (1483) described the disposal of the final effluent from septic tanks by irrigation in some rural or isolated areas, and Guiver and Hardy (1620) stated that the final treatment of sewage should be irrigation over grassland. Even though fertilizing benefits have been cited by Machenko (2806) for sewage effluent irrigation of potatoes, objections to disease transfer have been made by Mundel et al. (3122). Roberts and Jones (3639) reported that, when complaints were received on discharging sewage plant effluent into public areas, a community had purchased farm land for disposal by irrigation, and the land was leased for farming.

Treated effluents with the required quality have been reused by industry, e.g., 1.5 million gallons a day sold to an English steel works, reported by Barker (178); effluent from Moose Jaw, Saskatchewan, used by a Canadian oil industry for cooling purposed, described by Haack (1636); and the Corpus Christi, Texas, effluent (98% removal) sold to a refinery company as stated by Allison (57). Other uses for effluent of the proper quality were published: Dye (1055) noted the city of Tucson received more than $70,000 a year from the sale of effluent for irrigation and sludge as a soil conditioner; for hydraulic power generation (5137); boiler feed water (5088); or cooling water for a power station, (4988). Another possibility for disposal of waste water effluents from paper mills was reported by Southgate (4118). He concluded that to reduce pollution the various influent streams can be segregated, partially treated, and the effluent from these recirculated back into the industrial complex for use as washing water, in beaters, and for diluting stock.

Critique

Effluent disposal is one of the last steps in the operation of biological trickling filters. Systems to make economical use of the treated water have been designed. As the cost of pollution control goes up, more use will be made of recycle of effluents.

The biological trickling filter is only part of a total system to condition effluent for disposal. However, complex waste treatment problems have been solved simply and economically through use of the trickling filter, and in all probability its use will be continued. Limitations in the quality of effluent from trickling filters will require their use in combination with other systems. Designers should be encouraged to direct effluent disposal to other than water courses, especially if the treated effluent has valuable characteristics, e.g., an effluent high in phosphorus and nitrates being used for land irrigation.

Only recently has the literature indicated that control of effluent quality can be economically beneficial. More experience illustrating the economic advantages of effluent use and elimination of stream pollution should be reported, along with efforts to educate the public to realize the value of effluent reuse. The new more rigid stream standards will be a motivating force to develop better sewage treatment plants, in which the trickling filter may serve a useful function.

VENTILATION AND UNDERDRAINS FOR TRICKLING FILTERS

The design of the underdrain and ventilation system for the trickling filter has been the subject of many investigations and a large number of papers have been published on this topic. Much of this information resulted in the development of design guidelines, such as "Guides for Sewage Works Design" (5331). The Ten States Standards (5011) specify that, "the underdrain system, effluent channels, and effluent pipes should be designed to permit passage of air. The size of the drains, channels, and pipes should be such that not more than 50 percent of their cross-sectional area will be submerged under the designed hydraulic loading. Consideration should be given in the design of the effluent channels to the possibility of increased hydraulic loadings." The underdrain system was so interesting technically and economically that the Trickling Filter Floor Institute was formed to provide design information to assure proper performance of these units (5574).

Several investigators, such as Escritt (1191, 1201), published information on the specifications of underdrain systems and their construction. Lawton (2648) indicated that underdrain systems were well established in the early 1900's. Imhoff (2189, 2211) provided examples and design information on the size of a false bottom and to obtain sufficient aeration. Baltimore (5137) had a novel underdrain system, and the 18-foot drop of the effluent to the river generated power. As higher rate trickling filters were developed and the Biofiltration system was popularized, Nelson (3159), in 1943, stressed that ordinary percolating filters could not usually be adapted for Biofiltration, since the underdrain systems could not handle the increased flow of sewage.

Early work developed criteria on ventilation and the effect of porous walls, but Watson (4630) concluded that there was no benefit from open sides if sufficient air was circulating freely under the medium. In disagreement with Watson, Voorhies (4556) stated that the most economical trickling filter had open side walls to improve aeration. Furphy (1385) recommended that the air circulation should be sufficient to supply enough oxygen and carry off the carbon dioxide fast enough to prevent its concentration reaching more than 0.2%. Halvorson et al. (1665) disagreed with Weidlich (4662) on the function of air flow through a filter being dependent on the cooling or heating of the air by the liquid, change in density of the air due to change in humidity, and heating due to microbial activity. For dosages up to 20 million gallons the rate of flow of air is independent of the dosage and is a straight-line function of the difference between the temperature of the air and the sewage (1665). The aerodynamics of trickling filters was explained in considerable detail by Piret et al. (3389), who gave reasons for, and rates of, air movement under varying conditions. They, along with Benzie et al. (273), observed that in summer the sewage is colder than the air and the air moves down through the filter, whereas in winter the sewage is warmer and the air moves upwards; when the temperatures are about equal, very little air movement occurs. Studies in seventeen sewage plants in Michigan (273) showed that recirculation of effluent through a well ventilated filter in winter had a marked cooling effect and this reduced the efficiency of the filters by about 21%. The actual oxygen consumption was measured by Pönninger (3413) to be 6.5 to 7.5 grams per day per liter of biological film. Dahlem (853) stated that natural ventilation is sufficient if the filter is not too high, and these views were supported by Imhoff (2185). Petru (3342) supported the findings of Benzie et al. (273), and spoke of the cooling taking place in the effluent from the trickling filters, but thought it was caused not so much by external temperature as by the ratio of the filter diameter to the depth. Using Kr^{85} (as a tracer gas), Mitchell and Eden (3030) investigated ventilation rates in trickling filters and found that the controlling factors were the difference between ambient temperature and the temperature of the filter, the direction and velocity of the wind, and the elevation of the filter above ground level. Other investigators such as Chase (658) and Kolobanov (2543) emphasized the importance of the volume of air feed and system designed for adequate ventilation throughout the trickling filter.

When the temperature of the atmosphere and of the filter are the same, and when the strength of the waste is high, deep trickling filters with forced ventilation have been used to provide aeration by Galler and Gotaas (1397), Schreiber (3898), Halvorson (1667), and Imhoff (2182). In the following section, a detailed review of the literature is made on forced and natural ventilation for enclosed trickling filters. The quantity of air flow required under forced ventilation was studied by Lanz (2629) and Pönninger (3411). No advantage was shown by increasing the volume of air to more than 50 times the volume of sewage. Natural aeration (3411) could not supply the oxygen necessary for a unit treating a waste influent heavily loaded with concentrated sewage. Comparative studies were made of percolating filters under natural and forced ventilation conditions with and without effluent recirculation by Ziegler in Germany (4863). Deep-bed trickling filters arranged in layered section were reported by Ingram for controlled aeration (2222) and Schulz for forced aeration (3910). Controlled amounts of air were introduced (2222) to each section of the filter and provided the degree of treatment required. Schulz (3910) recommended a ratio of the filter diameter to bed depth of 1:6 with forced ventilation, while the data obtained by Ingram suggested at least a nine-foot depth should be provided for stabilization purposes. The use of forced ventilation by

Brown (492) adequately solved odor problems and increased efficiency, which was also verified by Galler and Gotaas (1397). Deep filters with forced ventilation were more economical than shallow filters, but only for high reductions in BOD, and they lost this advantage if pumping was required (1397). Many patents have been granted in the area of forced ventilation, e.g., Schreiber (3893, 3898), and Girard (1482). A brief review of artificially aerated trickling filters was published by Heilman (1860).

ENCLOSURES ON TRICKLING FILTERS

Shortly after the turn of the century, the Chicago Sewage Disposal Experiment Station (5308) found that trickling filters did not need a roof. Work at Pennsylvania State College over a fourteen year period (4578) clearly demonstrated that closed trickling filters were superior to open ones in efficiency, better oxidation, less odors, freedom from flies, algae, snow and ice, and from nozzle freezing. Ormsby (3248) showed that a closed filter gave greater bacterial reduction and an effluent with lower oxygen demand. Damm and Bock (859) reported in 1935 that closed trickling filters must have compressed air from above to treat dairy wastes; open filters have fly and odor nuisance. Enclosed filters were examined in South Africa by Hamlin (1690) using a Prüss-type enclosure, operating under the same conditions as an open filter.

In 1937, Böttcher investigated several methods to reduce the odor nuisance from sewage treatment processes in Berlin (418). He concluded that the least effective of the artificial biological processes, from a point of view of odor control, was the open trickling filter. If odor control was essential a plant with a closed settling tank followed by a closed trickling filter with sludge digestion and sludge drying in an enclosed centrifuge was considered the most desirable.

Performance Differences - Open and Enclosed Filters

Closed and open filters were compared in South Africa by Hamlin (1691) with only a slight difference in performance, contrary to the results obtained by Walker in the fourteen year study at Pennsylvania State College (4578). Hurley and Windridge (2112) described six months' experimental operation of two enclosed aerated filters. The purification obtained included BOD reduction of 95% and a significant degree of nitrification. For comparison, open filters treating the same sewage at half the hydraulic load produced a better effluent. However, if the open filters were required to mature at the same rate as the enclosed filters, the enclosed filters produced a better quality effluent. Mechanical parts might corrode more in an enclosed filter (4123).

Hamlin and Wilson (1693) stated that summer temperatures and dilution with storm water had considerably less effect on the enclosed filter than on the open one. In the discussion of this paper (1693), Scouller remarked that the percent of surface area left open was significant for operational efficiency.

Hurley (2110) found that operation of the enclosed filters without forced aeration lowered the effluent quality. Dahlem (853) pointed out in 1938 that complete enclosure and artificial aeration were not essential for the operation of trickling filters at high rates of flow. He gave importance to the size of the filter medium, the depth of filter suitable for natural aeration, free access of air to the bottom of the filter, good distribution of influent, and sufficient flow for rinsing action. Enclosing only the sides of the filter prevents the escape of flies and ensures good distribution of liquid over the surface. Complete enclosure is not necessary to control odor and overcome problems associated with cold weather. For the same population, an open filter two meters (78 in.) high and an enclosed filter four meters (156 in.) high would cost about the same to construct. Operational costs of the open filter are lower and the space required is greater.

In 1938, Blunk (373) was concerned that chemicals,such as chlorine for controlling nuisances on the trickling filter, were upsetting to the ecological balance. He thought that the fly larvae and other insects were part of the required fauna on the trickling filter and should not be destroyed. Loss of sunlight from enclosing the trickling filter is no cause for concern, since sunlight might lead to the development of organisms that are harmful to the biological processes. With the exception of the few light-requiring organisms, the ecology of the open and closed filters should be the same. Hurley stated (2111) that enclosed filters appeared to mature more rapidly than open filters. It was expressed that there is the possibility of severe corrosion resulting from the enclosure of mechanical plant parts.

In 1939, comparative tests of open and enclosed filters were conducted in Germany (5323). Wilson and Hamlin in South Africa (4748) pointed out that enclosed ventilated filters and an open filter at the Klipsperuit Works in Johannesburg, South Africa, could deal satisfactorily with nearly equal loads. However, in cold weather the enclosed filter could treat nearly four times as much settled sewage per cubic yard of medium per day as the open filter to give the same percentage purification. Husmann (2145) gave the various physical, chemical, and biological processes in conventional and high-rate filters. Enclosing the sides of a trickling filter allows ventilation to occur only vertically and accumulation of carbon dioxide in concentrations harmful to bacteria may occur. In completely enclosed filters, this carbon dioxide problem appeared to be serious enough to necessitate artificial aeration.

The main features of open and enclosed percolating filters used in South America were described by Barbeito and coworkers (189) and the advantages of the enclosed type discussed. Deep, enclosed, artificially ventilated filter beds in South Africa were compared with conventional open filter beds by Dekema and Murray (915). Over a three-year test period, the quality of the final effluent from the enclosed filter was slightly better than that of the effluent from the open filter. However, the enclosed filter was treating slightly more than two times the amount of sewage per cubic yard of medium as the open filter to about the same degree of purity. The enclosed filter was less affected by variations in atmospheric temperature and in strength of applied sewage than was the open filter. The operation of uncovered filters in North Dakota in cold weather was feasible, as reported by Stewart (4216). In 1948, Arnold (92) reported a comparison of the performance of two 6-foot filters at the sewage works of Grafton, North Dakota, which were identical, except that one was open and the other enclosed. Although temperature has some effect, the efficiency of open filters, as measured by the BOD_5 test, is slightly inferior to that of enclosed filters, even under severe winter conditions, and open filters are more effective during warm weather.

Hunter (2099) described an experiment on filtration of settled sewage through an enclosed percolating filter at Glasgow, Scotland. After the experiment had been in operation for two months, the filter was treating a hydraulic load equivalent of 388 gallons per cubic yard per day with purification equal to that obtained with open filters. However, ponding did occur in this enclosed filter in winter. In a discussion of the work by Hunter and Cockburn (2100), Lovett (2101) stated that the fungal growth in the enclosed filter could be due to the large volume of sewage applied per unit area. A paper in 1950 by Cameron and Jamieson (604) on the operation of the enclosed filter at Glasgow which developed fungal growth proved that good quality effluent could be produced at loading rates of 459 gallons per cubic yard. Aeration of the filter prevented the egress of flies and controlled slight odors. The superior performance of the enclosed filter was attributed to the grading of medium and the retention of heat.

Imhoff (2209) discussed the operational results of high-rate percolating filters in various countries, both open with natural aeration and closed with artificial aeration. Leibee (2671) pointed out the following advantages of enclosing percolating filters: (a) they will function better during cold weather, (b) ventilation can be improved, (c) odor and flies can be controlled, and (d) the contact of insects with the flora of the filter can be prevented. In well-designed open and covered filters in Minnesota, natural draft due to wind and differences in air density were observed to be sufficient to provide the air requirements, according to Johnson (2329) in 1952.

It was concluded from work done in South Africa (5358) that open filters with larger media showed less ponding and quicker recovery after reduction of load than did enclosed filters with smaller media. Nellist (3158) cited in 1965 the plugging of the filter medium of enclosed percolating filters treating waste waters from a coke works. Waste from other coke works has been treated by mixing 2% of the waste water with sewage prior to treatment on the percolating filters.

Tedeschi and Lucas in 1955 (4330) compared enclosed percolating filters with normal open filters, and noted from examination of the flora and fauna of the enclosed filter that numerous worms and larvae were present, algal growths were completely absent, and a large population of flies inhabited the air space under the cover. Pönninger described (3422), in 1957, modern developments and the design of enclosed tower trickling filters. In 1956, during parallel operation of uncovered and covered filters in Midland, Michigan, the covered filters were not less efficient than the uncovered (5645). Since maintenance problems of freezing and a considerable discharge of fog over an adjacent highway were experienced with the uncovered filters, the remaining filters were covered. Water, containing sulfides, was reported by Stone (4227) in 1962 to be made potable by means of biological filtration through a covered, coarse rock filter, followed by chlorination.

Critique

The above section may be summarized by noting that, after many comparisons of the operating data and results of open and enclosed percolating filters, no equivocal statement can be made. Covering of trickling filters has been shown to be an advantage under conditions of high organic loading, septic sewage influent to the plant, extremely low or extremely high atmospheric temperatures, location of the plant in a residential area and easier maintenance. Disadvantages of covering the percolating filters are the increased cost, specific wastes requiring artificial ventilation, difficulty in making large scale modifications to the distribution device or trickling filter and insulation from the summer heat which is reported to be helpful for trickling filter operations.

Temperature Factors of Enclosed Filters

Ingram (2226), Wilson and Hamlin (4745), and others (5637) quoted advantages of enclosure of the trickling filter for maintaining suitable temperatures. Wilson and Hamlin (4745) stated that the upper surface of the filter must be kept warm in winter and that the enclosure conserves this heat. Pönninger (3407) remarked that so long as the filter was kept free from sludge the results obtained were as good in cold as warm weather and that heating the air blown in was unnecessary. The heat created by the process of oxidation in the filter raised the temperature of the sewage by 1-2°C. However, to raise the temperature in winter, the upper sludge-collecting part of the filter should have air blown in from below, countercurrent to the sewage. Reddie and Griffin (3523) agreed that maintaining a higher temperature and aeration aided the ecology of the filter. Coste (795) observed the enclosure overcomes the cooling effect due to evaporation caused by free access of air through the filter. However, high summer temperature cannot materially assist the enclosed filter.

Wilson and Hamlin (4748) reported experiments showing 90° to 95°F. temperature to be optimum in obtaining good nitrification and effluent quality. Arnold (92) agreed with the observations of European investigators of temperature effect on open and enclosed filters. The open filter had slightly better removal during warmer months, but during winter months the open filter was inferior. The influence of temperature was discussed by Christ (683), who used an enclosed filter to treat paraffin oxidation plant waste. Bayley and Downing (226) studied the heat balance in percolating filters and concluded that the most important factor is the temperature of the applied sewage. The exchange of heat from the sewage with air, especially near the surface, and the production of heat by biological oxidation are also significant. Enclosed filters reduce the risk of freezing; however, the average increase in temperature would not be more than 3-4°C.

Critique

The temperature relationship of closed vs. open trickling filters has been explored, but more quantitative information would be desirable. Extrapolation of data from the various treatment of wastes in many different locations has been the basis of design for many years. Protection of the filter surface from the wind and cold helps keep the filter surface warm. The fast moving waste water being loaded onto the media has sufficient energy to keep from freezing, provided the added heat sink of wind velocity is controlled. The waste water temperature controls performance, not the temperature of the air.

Ventilation Factors of Enclosed Filters

Pönninger (3417) studied field operations and concluded that the use of aeration of high-rate trickling filters depends on the concentration of suspended matter in the sewage. High solids concentration will accumulate sludge on the filter, and artificial aeration on high-rate filters would be required to satisfy the oxygen demand. Blunk (372) stressed that downward air distribution through the filter rather than upward was desirable for the control of odor and filter flies. The rate of air supply to an enclosed filter was reported by Dekema and Murray (915) to be varied within the range of 0-1.96 ft^3/min./yd^3 of filter medium. They also noted that there did not appear to be any direct relation between the quantity of air supplied and the performance of the filter; however, there was a limit below which the efficiency of the filter deteriorated. Pönninger (3421) cited some advantage in long rest periods for percolating filters which were covered and aerated. He previously did experimental work (3407) with the direction of flow of air opposite to the flow of sewage, and reversing in winter to warm the air, in the operation of an enclosed, nonplugging biological filter. The volume of air was maintained continuously at 30-40 times the volume of sewage over a 24-hour period. The capability of reversing the flow of the air was useful.

Concern was expressed by Bach (123) that carbon dioxide build-up in the air space of an enclosed trickling filter would limit the normal biological growth. Hurley and Lovett (2113) studied enclosed trickling filters with and without aeration and concluded that the conservation of heat obtained by enclosing the filter more than counterbalances the cooling effect of the air blown into the bed. It was further suggested that a shallow enclosed filter 6 feet deep could be used for partial treatment with about 50% purification. Hurley and Windridge (2112) described experiments based on the operation of two enclosed filters without forced aeration. The quality of effluent decreased appreciably in the absence of aeration. The treatment of dairy waste was reported by Trebler et al. (4444), using large enclosed filters and open filters with artificial aeration. A rather unique medium for their filter was empty condensed milk cans, which allowed easier movement of the air. Hamlin and Wilson (1693, 4748), in a series of papers on percolating filters, noted that artificial aeration produced more stable operation. Comparative costs for different types of covered percolating filters were given and discussed. Artificially aerated filters were suggested by Wuhrmann (4831) to be used in series operation with highly loaded activated-sludge plants, taking advantage of the existing compressed air capability. No relation was found between the efficiency of the filter and the intensity of aeration. He concluded that with a deep filter neither artificial aeration nor covering was necessary.

Critique

Forced air ventilation may be required for strong waste waters or adverse conditions. For municipal and low industrial waste waters, natural ventilation should be adequate. Much research and development have not firmly established the exact quantity of air flow required for optimum operation. The direction of air flow is preferably downward in the direction of liquid flow. For deep beds, it is understandable that covers and forced ventilation are not required. However, caution is suggested in using uncovered filters in severe weather conditions, because the distribution system may still freeze.

Natural Ventilation in Enclosed Filters

References to the literature were given by Imhoff (2209) dealing with natural aeration on open filters. Johnson (2329) reported in 1952 on studies of natural flow of air through percolating filters in Minnesota. Comparatively low rates of flow of air were adequate to supply sufficient oxygen to reduce the BOD by 85 to 90 percent. Whitehead (4745), in discussing the work of Wilson and Hamlin (4748), was of the opinion that there was more scope for improved operation in using naturally ventilated filters in alternating series than normal operation with forced ventilation. An enclosed percolating filter known as the "Natural Draught," as discussed by Tedeschi and Lucas (4330, 5637), performed well in treating industrial as well as domestic waste waters in the neighborhood of 500 gal./yd^3/day. Some molasses slop wastes, reported by Krige (2571) to have been treated by enclosed percolating filters under natural aeration conditions, were inadequately treated due to the high organic suspended solids loading. Aeration of the slop in admixture with domestic sewage was also not satisfactory.

Critique

Natural ventilation is adequate under lightly loaded conditions such as a conventionally loaded municipal waste treatment trickling filter. Increases from the normal organic and hydraulic loadings may require forced ventilation or aeration to achieve the desired BOD level.

Forced Ventilation with Covered Filters

Several technical papers, e.g., those of Hurley (2110, 2115), Husmann (2136), Guilbert (1618), Imhoff (2209), and Mohlman (3051), have been published on the various aspects of using forced ventilation with covered low-rate and high-rate percolating filters. The papers, in general, cite the advantages of this concept, but are quick to point out that specific cases of low solids concentration or dilute waste water made enclosure or forced ventilation of the filter necessary.

Several patents on methods of forced aeration and enclosure equipment have been issued. Typical is that of Girard (1482) for forced aeration. A patent to Brintzinger (463) used forced aeration through granular burnt pyrites media. Griffin (1598) was issued a patent for uniform aeration as a means of preventing clogging. Griffin (1597) was also granted a patent in which air is passed through successive chambers in the same order as the sewage, and is not liberated until the liquid has reached its maximum degree of purification. Dekema (914) developed a patented process for passing the sewage or other impure liquids downward through a series of enclosed filters into which air was injected at a controlled pressure. This method provides for changing the order of the filters to permit cleaning the medium. Blunk (369) obtained a patent which revealed a sewage filter with an impervious wall and roof so that air can be drawn or forced uniformly upward through the bed and discharged through ventilation shafting. Prüss and Blunk (3477) developed two patents on the purification of trade wastes and sewage. The liquids are forced into a closed space above a filter bed and distributed over the bed. Air is also forced into the closed space under pressure, and liquid and gases separated below the bed, paying particular attention to the hydrogen sulfide balance.

In the period of the late 1930's and the early 1940's, there was considerable activity in the development of forced ventilation of an enclosed trickling filter. Papers on the Prüss-type enclosed trickling filter, e.g. Antill (82), and general surveys of the type of equipment used, e.g. Sée (3955), evaluated the effectiveness of enclosed trickling filters with forced ventilation. Hurley and Windridge (2111, 2112) presented a paper at a meeting of the Institute of Sewage Purification in 1938, which generated much discussion and indicated the advantages of enclosed filters, e.g., maturing more rapidly than open filters, and requiring forced aeration to maintain a good quality of effluent. Pönninger (3414) was concerned with the amount of sludge being added to the enclosed percolating filters and recommended that a medium of suitable size be used in conjunction with periods of aeration without the addition of sewage. Pönninger also emphasized (3407) that the direction of the flow of air under the forced aeration conditions was important and that by forcing the air to go in the opposite direction to the waste some operational advantages may be gained, especially in winter. Hurley and Lovett (2113) worked with deep, shallow, enclosed filters and found that deep covered filters may: (a) treat four to five times as much sewage as open filters which were brought into operation at the same time and were not yet matured, and (b) treat about three times the flow treated on mature open filters. Blunk's findings (373) that the forced aeration should be from the top down to handle the odor and fly problems agreed with those of Pönninger (3407). The carbon dioxide concentration was acknowledged as a problem by Husmann (2145), who asserted that sufficient air should be supplied to trickling filters to maintain the activity of the aerobic bacteria and prevent harmful accumulation of carbon dioxide. Concern expressed by some investigators regarding the carbon dioxide concentration was minimized by Hamlin and Wilson (1693) in studies which determined that carbon dioxide was not injurious and the necessity for adequate ventilation was not related to the carbon dioxide removal.

Operations in South Africa by Dekema and Murray (916) indicated the effectiveness of the alternating double filtration process using enclosed forced ventilated filters. Upward ventilation gave slightly better results than downward ventilation, but more power was required and the nuisance factors were greater. The same authors (916) concluded later that this alternating double-filtration process was capable of, as he defined, a "purification capacity" of 3.2 compared with 2.3 for a single enclosed filter, with the reference of 1.0 for a single, six-foot open filter. Factors affecting the efficiency of covered percolating filters used in the treatment of waste waters and sewage were reported by Yonner (4842), with particular reference to the von Roll system of forced aeration.

Many plants were built using the enclosed forced ventilation trickling filter. Examples of these were the treatment of dairy waste as recorded by Damm and Bock (859), of municipal waste in South Africa [Hamlin (1690)] and in Glasgow [Cameron and Jamieson (604)], of waste water from abattoirs in France [Planchon (3393)], of municipal-industrial waste in Germany (5250), at a waste treatment plant located near a residential section in Minnesota [Bardwell (172)], or recent plant expansions in Transvaal [Barnard (179)], and treatment in western France and Normandy [Guilbert (1617)], to mention just a few. Enclosed aerated trickling filters have been used instead of the activated-sludge process for secondary treatment of sewage on the upper Ruhr, according to Prüss (3475). Imhoff tank and septic tank effluents have often been treated by enclosed aerated trickling filters, e.g. Rohde (3668) and Davies (880).

Critique

Forced ventilation has been successful in many industrial applications of enclosed trickling filters. Evidence has pointed to the organic strength, suspended solids and hydraulic loading as factors to be considered when questioning the desirability of forced ventilation. Most municipal wastes being treated on conventional depth filters (6 to 8 feet deep) require little or no forced ventilation. Forced ventilated filters may be necessary during peak flows and more controllable at stable atmospheric conditions. Air requirement of the activated-sludge process is in general more than that of aerated trickling filters. The importance of good quality effluent governs the economics of aerated filters.

ECONOMICS IN DESIGN

Cost reporting was practiced early in waste treatment history, e.g. by Clark (690), and was the basis for economical designs. Many investigators such as Smith and Ellison (4072), Anderson (74), and Sullivan and Wiley (4267) emphasized the significance of an economical design and some of the factors involved. Metcalf and Eddy (2983, 2984) reported in their texts, "Sewerage and Sewage Disposal" and "Disposal of Sewage," the principles of methods of financing, construction, and operation of sewage works, along with some process cost data, to provide a basis to the young design engineer. Later, texts by Babbit and Bauman, "Sewerage and Sewage Treatment," (112), and by Besselièvre, "The Treatment of Industrial Waste," (308) continued this effort to modern times.

Calvert (595) reported on the wide variation in unit costs of sewage treatment works,depending upon the cost of construction of the plant, the site, equipment required and other facilities of a variable nature. Thoman and Train (4359) reviewed previous studies on the estimation of costs for municipal sewage treatment and gave an illustrated description of the use of generalized cost curves in planning a pollution control program. They also illustrated how this information had been gathered previously and evaluated, based on limited information. Reference was made to previous work by Velz (4534) as well as other investigators, and to the comprehensive U. S. Public Health Service compilation (5595), in which generalized cost curves of trickling filters with separate sludge digestion (Figure 7) and Imhoff-type plants (Figure 8) were developed, showing the cost per capita versus the population served. Cost data on industrial waste treatment were at best meager (2145), and, therefore, generalized planning was difficult since there was no basis for extrapolation. The use of Engineering News Record's Cost Index, based on 1913 dollars (4359), was recommended in determining estimated costs for planning purposes. In an effort to bridge the lack of information on industrial waste disposal, Stack (2224) introduced modifications to the equation previously developed to express the performance of biological filtration and to illustrate the relation of filter design to the economics of the process. Economics of design

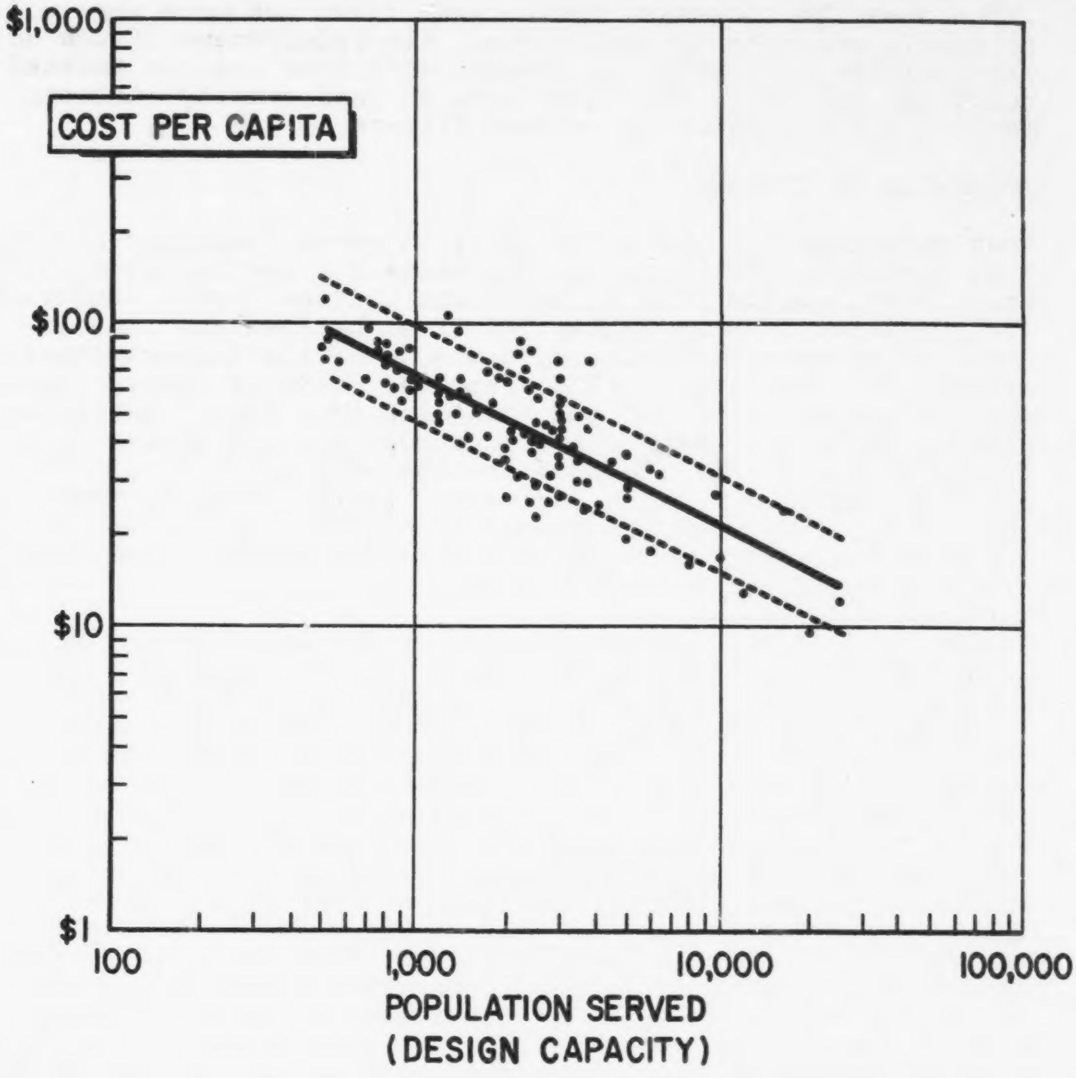


Fig. 7 - Construction Cost per Capita for Trickling Filters [by Permission of U.S. Public Health Service (5595, p. 16)]

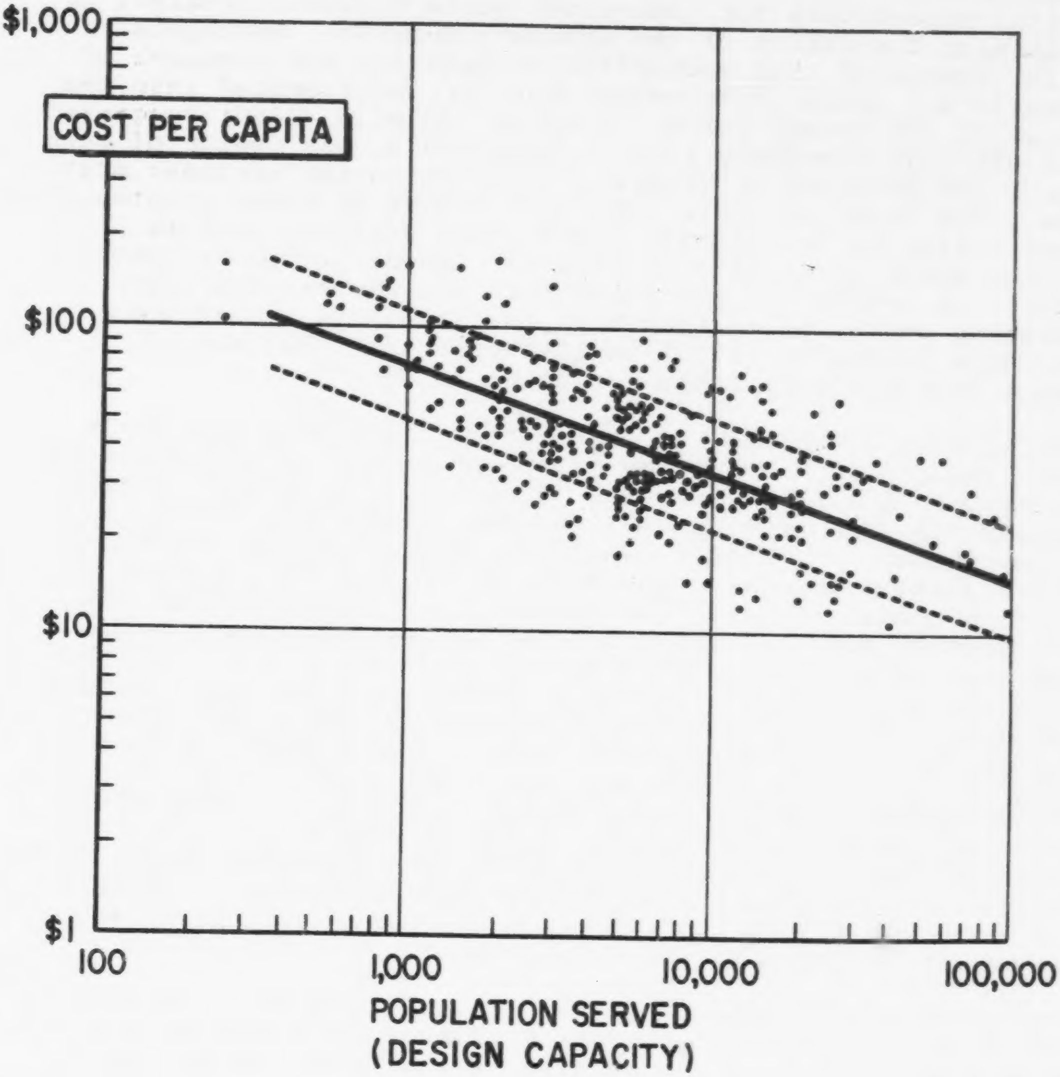


Fig. 8 - Construction Costs per Capita for Imhoff Sludge Digestion Plants [by Permission of U. S. Public Health Service (5595, p. 17)]

were considered by Rankin et al. (3501), Biddle and Hoffman (324), and the Trickling Filter Floor Institute (5574). Besselièvre's textbook, "The Treatment of Industrial Waste," (308) stresses the importance of economics in operation and capital expenditure for industrial waste treatment design. In explaining the duties of the sanitary engineer, Southgate (4128) specified that economical methods for the disposal of domestic and trade waste waters must be incorporated into the design of the sewage plant. However, Schelle (3860) suggested that effluent standards created problems in the design of such plants and problems in financing with which the engineer must cope. The usual economic condition sought in waste treatment plant design is to minimize operational expense, such as pumping costs or artificial aeration, as described by Imhoff (2205). A common and preferred practice was to have high operating costs rather than high initial installation cost, according to Hansen (1718) in 1942, for the treatment of sewage from military camps during World War II.

The decision to go one way or another on a design for large installations in Chicago has often been based on economics as reported by Eddy and coworkers (1093). The activated-sludge process was used here rather than the Imhoff-tank trickling filter system. Pönninger (3410) in 1938 evaluated trickling filter designs from the viewpoint of the greatest economy in building costs. Process design and plant modifications with economics in mind have been published for many years; e.g., Voorhies (4556) noted that the most economical layout of the plant was to place the trickling filter entirely above ground; Gascoigne and associates (1427) concluded that a new type of biochemical process would cost less to build than activated sludge or trickling filter and operational cost would be between them; Jackson, in a chapter in the book, "Waste Treatment," edited by Isaac (2238), found it economical to salvage an animal food from distillery waste, and Tiedeman (4392) and Collom (763) evaluated the cost and effectiveness of chlorination in conjunction with trickling filters. Many other examples can be found in the literature.

Many of the early reports in the literature simply stated the cost of construction or operation of a waste treatment plant and the population it was serving, e.g., Doten stated that a septic tank trickling filter plant for a population of 2,000 cost $8,000 in 1919 (1005); Hartley in 1914 published the cost of an Imhoff-tank sprinkling filter plant as in excess of $18,000 for a population of from 300 to 1,200 people (1762); operational cost of a 3-million gallon a day plant was slightly over $5,000 in 1913 and almost $6,000 in 1914, based on an initial investment of $189,000 for a population of over 20,000, according to Eddy and Hammer (1089). Schreiber in 1942 (3893) described the cost of construction of his "SU" trickling filters to be 4,000 German Reich marks per thousand cubic meters of sewage treated daily.

Relative economic information was detailed by Wilson and Hamlin (4746). Construction of an enclosed filter is about eight times more expensive than an open filter, and the medium is about three times more expensive than for an open one. Relative economics were reported by Jenks (2305), e.g., construction costs for a Biofilter were slightly more than for an activated-sludge plant and one-half to two-thirds those of a trickling filter plant, while power costs were generally double those for a trickling filter and one-half those of an activated-sludge plant. Chipperfield (679, 681), while developing a case for the use of plastic medium trickling filters, reported (a) 48% savings in capital cost compared with conventional medium filters and 24% compared to activated sludge for a strong carbohydrate waste, (b) 28% savings compared to conventional filters on a distilling waste where activated sludge proved to be impractical, (c) 40% savings compared with conventional filters on a brewing waste where activated sludge, also, was impractical, and (d) 55% savings compared with a conventional filter on a food processing waste. Several investigators, such as Chalmers (647) in 1967, developed various formulas for calculating cost of treatment of waste waters from food manufacture and coffee processing.

A separate sewage system for the treatment of hospital waste would reduce the operating cost of a municipal treatment plant. Poole (3423) described methods for reducing cost; e.g., changes in plant process, reuse of waste water, inexpensive types of treatment, and reducing the amount of mechanical equipment required. Economics for minimum capital expense were established by Smith and Wittenmyer (4086), Bischofsberger and Wurm (335), and Herriot (1899) during their design of biological treatment plants in this country and Europe. Several modifications, such as the Emscher tank in combination with percolating filters, have been reported by Böhnke (388) and Kehr (2413) to reduce the cost of the waste treatment plant and simplify operations. Many of the published papers contain detailed design, construction costs, and tables of operating costs, e.g., Weller (4673), Brühne (509), Anderson (78), Borrie (411), Fernie and Utting (1256), and Moss and Mengel (3101).

In several publications, such as that by Hepburn (1889), the trickling filter was compared economically with other processes. He concluded that activated-sludge plants occupy smaller areas than trickling filters, cost less to install, but cost more to operate, and required skilled supervision. Goudey (1525) after surveying the added benefits of sprinkling filter plants, concluded that the improvement in suspended solids and BOD removal was not sufficient to justify the increased cost of trickling filters. The cost of installation and operation was estimated to be $100,000 mgd capacity and $10/mg for the sprinkling filter plant versus $25,000 installation and $5 operation for separate sludge digestion, and $60,000 installation and $15 operation for the activated sludge process. Operational costs of 42 southeastern trickling filter plants were calculated by Franzmathes (1344) and related to expanding flow capacities. German investigators, such as Pöpel and Daser (3427) and Schreiber (3894), published the comparative cost of construction and operation on a basis similar to investigators in the United States, such as Ellsworth (1162) and Montgomery (3074). As additional economic factors, several investigators, e.g., Imhoff (2212), Hipwood (1958), Pruss and Blunk (3474), and Calvert (591) noted the land area and location of the waste treatment plant relative to population centers.

Critique

It would seem that the area of economics in design would be extremely clear-cut with answers prepared for most circumstances. This would appear especially true since much of the capital spent for waste treatment was public funds, all of which should be well justified. Unfortunately, waste treatment, like city planning, crept upon this complex society and only a few of the forward thinkers were able to build logical, economic, well-designed plants and systems.

The results of the work of various agencies in this country and abroad were made available so that the cost of treatment of a million gallons of waste could be evaluated for the next design problem. One difficulty in economic comparisons is finding a common base. The workers have dutifully reported their installation operational costs. However, the investigation to compare one city with another or, even worse, one industry with another, to determine an economical design, has only been initiated.

Papers on units such as the cost of a pound of BOD removal or the cost of a foot of hydraulic head have been submitted, but not widely used to relate economics to design. The day is past when the engineer's design is beyond reproach. Competition is keen and only the lean, efficient, reliable design is sought. With computer inventory techniques and heavy Federal financing, it should not be surprising that bases for economical design will be established in an effort to choose the best and most economical.

SECTION IX

CONSTRUCTION TRENDS

Selected papers are noted below, indicating the type of treatment plants which were constructed throughout the various decades. Information on other construction aspects is included, such as reports on prefabricated or package plants, construction materials, and other considerations. Several general reviews of construction were available in the literature, e. g. Knox (2532), Pearse (3326), Hyde (2157), Escritt (1190), Daviss (892), and Friel (1355), with some evaluation by the authors. At a general meeting, sanitary engineers (2449) discussed the trends in the methods of waste treatment in Great Britain and the influence of these trends in equipment and instrumentation development.

DECADES OF TRICKLING FILTER CONSTRUCTION

In the decade prior to the turn of the century, complete disposal of sewage, apart from screenings and inorganic matter, was thought to occur by using contact beds or by the aid of septic tanks. As more was learned about the bacterial treatment of sewage, it was acknowledged that these processes were not optimum. In the decade between 1900 and 1910, more modern forms of tanks were developed and experience with trickling filters was gained (5059).

In 1892, experiments by Dibdin at Northern Outfall Works at Barking Creek, Great Britain, were begun, resulting in the development of fine contact beds (946). Fine contact beds were modified into coarse contact beds at Sutton which were later used as trickling filters at Exeter (946).

1910 - 1920

For the period 1910-1920, the treatment plants in England were characterized by detritus tanks, settling tanks, trickling filters, and humus tanks, as reviewed by Marsland (2870). The Kelowna, British Columbia, treatment plant consisting of Imhoff tanks, percolating filters, and sedimentation tanks was described by Meckling (2951). Sewage plants using covered septic tanks with effluent discharge onto intermittent sprinkling filters (5441), or mechanical screens, Dortmund tanks and storm water tanks (5058) were also constructed during this decade. Hansell (1712) described the construction of a 16 mgad (368 gal./ft^2/day) waste treatment plant at Atlanta, Georgia, which included coarse screens, grit chambers, Imhoff tanks, fine screens at one of the plants, and roughing filters at the other, dosing tanks and ventilated percolating filters. An interesting plant (5459) was built at Prescot, England, on the basis of the Travis theory of the dissolution of sewage solids and consisted of a series of sand pits, screens, detritus tanks, a "hydrolytic tank," primary and secondary filters of clinker and final settling tanks. A special feature of the hydrolytic tank (5459) was the self-cleansing colloidors, the function of which was to remove the finely divided suspended solids and colloidal matter by surface contact. McDonnell (2908) supplied an engineering description of the plant at Sedalia, Missouri, which operated on a combined sewer system and handled the sewage of 20,000 people. The plant was comprised of grit chambers, Imhoff tanks, dosing tanks and sprinkling filters with a surface area of 0.6 acre and 5.5 feet deep. The 1914 sewage treatment plant for Madison, Wisconsin (5052), was designed for a population of 25,500 and comprised of settling tanks, a sludge digestion tank with a contact dosing chamber and sprinkling filters, followed by shallow secondary settling basins. Buchler (519) described the construction in 1913 of the sewage system for Singapore to treat the waste of 300,000 people. The plant consisted of screens and detritus tanks, 32 Imhoff tanks with two- to three-hour retention, 55 coal filter beds, each 100 feet in diameter and 6 feet deep, and humus tanks with about two hours retention. Patents were issued to Girerd and Drapier (1484) and Girerd (1485) in 1906-1907 on the trickling filter process.

1920 - 1930

During the period of 1920 to 1930, Russell (3793) described the new southwest sewage treatment plant at Springfield, Missouri, which was designed to serve 47,500 people and consisted of screens, grit chamber, settling tanks equipped with revolving sludge scrapers, sprinkling filters and sludge digestion tanks, the effluent being discharged into Wilson Creek. Similar plants were built at East Rochester, New York, according to Skinner (4044), Baltimore, Maryland, described by Keefer (2388), and Rothwell Yorks, Great Britain, (5464), with some modification of settling equipment. Hart (1754) reported on the sewage plant at Leeds, where chemical precipitation was used preceding trickling filters. The waste from the population of 650,000 with 598 mg/l suspended solids was treated by this method. The chemical precipitation plant at Teddington was modified into percolating filter treatment with the construction of five new filter beds. The reason for greater adoption of the activated-sludge process in America than in England was suggested by Morling (5463) to be due to the average strength of the English sewage being greater than that in America. Chemical treatment of the sludge from a standard percolating filter plant (5263) rendered it acceptable for a fertilizer. In the Berlin area (5238), where local regulations permitted free irrigation, this method was satisfactory. Storm water tanks in conventional percolating filter plants were used routinely, e. g., by Silcock (4025). Construction of trickling filters with and without enclosures was reported by Walker et al. (4579).

Imhoff tank-trickling filter plants were described by Montgomery (3070) to provide adequate treatment for Wichita Falls, Texas; a similar plant served Cleveland, Ohio (5099). However, the Imhoff tanks put into operation at San Bernardino, California, were eventually converted to two-stage digestion tanks due to an increased flow and required plant expansion, according to Livingstone (2727). Imhoff (2190) discussed the construction and operation of the trickling filter plant in Moskau-Koschukodo. These plants were designed to operate with artificial aeration through boiler clinker media 2.5 to 5 cm (1 to 2 in.) in diameter and the surface load of 0.95 meter/hour, following a short aeration period by activated sludge ahead of the trickling filter unit. Mathews (2884) in 1928 stated that there were three kinds of filters, i. e., sand filters, contact beds and percolating filters, and with all three the requirements for satisfactory operation were sound filter media, uniform dosage, sufficient aeration and proper underdrainings.

1930 - 1940

As indicated by the literature, the decade between 1930 and 1940 was a time of high productivity and construction. Bowe (424) discussed the reconstruction and enlargement of the New Canaan sewage works, which involved the addition of auxiliary equipment for aeration, solids-liquid separation and sludge dewatering. Typical of the many plants built was that at Mason, Michigan, described by Shephard (3988), which was comprised of a grit chamber and bar screens, two primary settling tanks with a detention period of 196 minutes, two trickling filters with ventilating fans to improve aeration, final settling tanks, digestion tank and glass covered sludge drying beds. Ellipitical concrete domes were used to cover the sewage filters at Hibbing, Minnesota (3056). At Marcy State Hospital, New York, separate sludge digestion (to avoid grease scumming) along with trickling filters, secondary settling tanks, and chlorination equipment were constructed to handle the flow for a population of 5,000 according to Ryon (3805). WPA labor was used, according to Tatlock (4301), to construct the Dayton, Ohio, trickling filter plant. In 1935, out of 85 sewage treatment plants either completed or in the course of construction, 41 were with sedimentation and separate sludge digestion, 26 were modified Imhoff plants, 11 were activated-sludge plants, 4 used sedimentation and trickling filters, 2 plants used plain sedimentation and one was a septic tank plant (5319). A national census of sewage treatment projects (5322) indicated that in 1939 a total of 848 plants were built which represented an increase of 18% on the total of 4,700 plants in service at the beginning of 1939. The trends during this era in sewage treatment were for separate sludge digestion, the activated-sludge process, and trickling filters (high-rate and Biofilters).

Dunbar filters were used by Thackwell (4349) at Tyler, Texas. The plant, which was designed for an average flow of 0.6 mgd

(13.8 gal./ft^2/day) and a maximum flow of 1 mgd (23 gal./ft^2/day), was comprised of a grit chamber, bar screen, hydraulic pump, vacuum chlorinated effluent, multiple hopper bottom settling tanks (1.5-hr detention), heated sludge digestion tanks, glass covered drying beds, primary and secondary Dunbar filters, and a step aerator.

Imhoff tank-trickling filter plants were still being built in 1938-1939, such as that at Hoopeston, Illinois (1947), to replace septic tank-land irrigation plants. The waste treatment plant built at Hamilton, New York, prior to 1931 consisted of a pumping station, preliminary settling tanks, sludge digestion tank with floating cover gas collecting dome, a glass-covered sprinkling filter, an open final settling tank, and sludge drying beds plus a short submerged outfall sewer.

Construction in England was represented by circular trickling filters with rotary distributors, described by Hurley and Chibbett (2109), and efforts to use settled effluent on percolating filters without chemical treatment (3095) were similar to efforts in this country. Legal pressure was brought to bear and resulted in the construction of additional filters at Peterborough, England, to treat sugar beet factory waste (4953). The sewage works at Truro were reported by Barnes (181) to consist of a grit and screen chamber, pumping station, settling tanks, trickling filters, humus tanks, storm water tanks and sludge beds, which were designed to treat six times the daily dry weather flow from a population of 12,000. Oliver (3231) reported on the construction and operation of the Buxton sewage disposal works. The use of roughing filters and chemical addition satisfactorily treated the waste. Understanding of the construction of trickling filters and activated sludge systems was reported by Reichle (3536), as the advantages and disadvantages of the two processes were noted and the combination of the two processes was recommended for some wastes. Construction in England was reported by Honey (2004) to involve the use of screens, detritus channels, hopper bottom upward-flow settling tanks, storm water tanks, sludge dewatering tanks, uncovered digestion tanks, and sludge drying beds. Prior to World War II, satisfactory results were obtained from several small treatment plants which were soon overloaded. Conversion of the smaller plants was described by Mills et al. (3016). Areas such as Romford and Hornchurch, according to Snook (4092), and Sanlesbury kept up with their increasing population and sewage load by addition of more percolating filters, Dortmund humus tanks, and storm water handling capabilities.

Construction in Germany (4257), (3397), Argentina (24), and Canada (801) was indicative of the world-wide activities to treat various waste waters. These activities involved enclosed trickling filters, activated sludge in series and parallel, replacement of outdated septic tanks and irrigation systems, and repairing and upgrading existing facilities to provide the degree of treatment necessary in each locale. Activity in Rio de Janeiro was slightly different than that experienced in many parts of the world (5089). The construction and operation were by a private company which owned the sewage system and used chemical-biological treatment as well as no treatment at all to handle the waste from 92,000 homes.

1940 - 1950

In the period of time between 1940 and 1950 many of the reports were involved with the modernization of waste treatment facilities, e.g., the paper by Bragstad (440). Allen (51) published the flow diagram and description of the sewage plant at Regina, Saskatchewan, which treated the combined trade waste waters and municipal sewage from a population of 55,000 people by sedimentation, biological filtration and activated sludge. New plants were constructed at Lebanon, Tennessee (5435), and plant extensions were made at many cities, such as Stockton, California (2651), and Auckland (5215), to upgrade the degree of treatment. Biofilters were used often, e.g., at Minneota, Minnesota (1963), and Santa Maria, California (2892), in combination with normal grit removal and primary sedimentation. The plant at Santa Maria also used a Vacuator in an effort to remove the suspended solids by flotation. Construction in Brazil involved the use of Imhoff tanks, chemical treatment, treatment by the activated-sludge process, percolating filters or a combination of the processes (1463). Industrial wastes were treated using recirculating high rate filters, according to Eldridge (1141) and Kirchoffer (2494). The general developments in industrial waste treatment, along with their legislation, were reviewed by Russell (3790) in light of the progress made in the design, construction and operation of sewage treatment plants.

In this period, the literature indicated projects were constructed for different reasons. The motivation, such as that at Neosho, Missouri, described by Smelser (4056), was due to the increase in population by the establishment of a military camp. Sewage works at Broken Hill, Great Britain, were under construction (consisting of coarse screens, primary settling tanks, two secondary settling tanks, four trickling filters with humus tanks, and four digestion tanks), but was stopped August, 1942, with the understanding that it would be completed after the war (5012). Other construction specifically aimed at supplying services to the war effort was reported (5107), such as the construction of the waste treatment plant to handle sewage at the War Office Building in Arlington, Virginia. This plant was comprised of aeration tanks, high-rate trickling filters, final settling tanks, heated sludge digestion tanks, and glass covered sludge drying beds. Workers in the field adopted the attitude, as discussed by

Siebert and Milligan (4015), that war time pollution problems were to be solved with the minimum use of strategic materials, e.g., the percolating filters were made without sides or with sides of any material available such as rubble or unreinforced concrete.

1950 - 1960

Construction activity, from 1950 to 1960, was extremely vigorous as war time restrictions were relaxed and the Robert A. Taft Sanitary Engineering Center, of the United States Public Health Service, was opened as a research facility. Plants were generally constructed on conservative lines emphasizing secondary treatment, disinfection of effluent, and high-rate percolating filters. Also, the growth of the activated-sludge process was encouraged and industry was taking an active part in developing methods for the treatment of trade waste water (4913). A common situation was that expressed by Uzzle (4504) for Hickory, North Carolina. After the war, the waste treatment plant was overloaded and reconstruction increased its capacity. The Atomic Energy Commission (327) built the first full-scale plant for handling radioactive wastes which was composed of mixing, primary sedimentation, biological filtration with recirculation, secondary sedimentation, chlorination and sub-surface disposal.

In answer to the demands of the housing boom, construction of waste treatment plants for subdivisions was reported by Greenleaf (1575, 1576), and Rader and Associates (5418), to consist of primary sedimentation, biological filtration, final sedimentation, effluent chlorination with Imhoff tanks and sand filters or separate sludge digestion, depending on the quality of effluent which was required under local conditions. Voters backed the construction of new waste treatment plants in Perryville, Missouri (4807), and of adequate facilities in Charlottesville, Virginia (1708). The sewage works often became a showplace of the communities, such as at Long Beach, New York, (3660) and Easton, Pennsylvania (1890). However, these waste treatment plants were built along rather conventional lines, e.g., at Charlottesville, Virginia, the plant, which served a population of approximately 18,000, was comprised of a barminutor, detritus and primary sedimentation tanks, percolating filters, chlorination and final sedimentation tanks, primary and secondary sludge digestion and sludge drying beds. New developments were incorporated into designs to satisfy specialized conditions, such as high oxygen demand, as reported by Lindsey and Smith (2721). Sludge washing and thickening at Caldwell, Idaho, were noted by Reynolds (3564), along with comminutors and centrifuges, which were indicative of the popularity gained by mechanical equipment. However, low cost operation was still a desired construction goal, as exemplified by Noble (3192) by the plant built at Vernal, Utah, which was, essentially, a conventional percolating filter plant. Continued activity in the treatment of industrial waste in the form of plant construction was reported by Ackerman (9) for a specialty paper mill. The literature (277, 833, 1837, 1884, 2926, 4480, 4838, 4849) is extremely replete with articles dealing with expansion, reconstruction, modernization, and updating of existing waste treatment plant to meet initial legal guides established. There was no particular problem, as reported by Klassen and coworkers (2503), in normal waste treatment plants handling ground garbage discharging into the sewers, which became popular equipment.

Combined industrial and domestic plants were fairly common, e.g., Charlotte, North Carolina (1340). City-industrial cooperation to develop new waste treatment facilities which provide the higher degree of treatment necessary was cited by Thomas (4363). Construction of a new treatment plant at Dexter, Missouri, was reported by Ross (3694), and the downstream farmers no longer complained about pollution of the creek receiving the effluent and benefited by using the dry sludge as fertilizer.

Efforts similar to those experienced in the United States were reported overseas, such as the publication of the British Standard Code of Practice which was used as a construction guide for waste treatment plants (4952). Plants were expanded and modified extensively in many locations in England, such as Calne (1839) and others. These waste treatment plants were equipped with sedimentation tanks, chemical treatment tanks, percolating filters, humus tanks, sludge removal by monorail at Bisley (5025), alternating double filtration at Liverpool (5219), modification of sand filters at Wisley (4289), abandoning of cramped facilities and reconstruction at Taunton (4494), incorporation of storm water treatment including some trade waste waters at Bromwich (5532), and sludge from the alternating double filtration plant at Lundwood was used to produce gas for generating electricity (5270).

Elsewhere in Europe, activities were similar in the expansion and renovation of existing waste treatment plants and new construction for overloaded areas, such as that reported by Haury (1811) for several German communities. The Heilbronn waste treatment facility, described by Pöpel and Daser (3426), added biological filters, and an aeration tank with the necessary appurtenances was modified. The construction in Germany in the post-World War II period indicated the trend to more secondary treatment and beneficial uses of digested sludges for power, fertilizer, or fill material (67, 470, 3426). New construction of sewage disposal plants in South Africa was also continued and, typically, was reported by Hamlin to be (1696) treatment by primary sedimentation, biological filtration, final sedimentation, and filtration of the effluent on reversible sand filters. Percolating filters were used in Switzerland along with activated-sludge processes for handling populations from 1,000 to 16,000 inhabitants plus industrial waste waters (4927). Construction of sewage plants at Bad Vöslau, according to Kreuth (2569), was comprised of screens, two Emscher tanks, two covered percolating filters, and secondary sedimentation tanks to handle the waste water from 6,000 inhabitants. A new sewage treatment plant built for Oshawa, Ontario, was described by Reilly (3550) as a standard biological filtration plant with the effluent discharged to a lagoon prior to discharge to Lake Ontario.

1960 - Present

The literature from 1960 on represents activities in legislation and in further construction and modifications along similar lines as that of the 1950's, with a few modified processes being built. Expenditures for construction of waste treatment plants were reported by many, e.g., the staff of Water and Waste Engineering (5647) in 1966. Laws similar to those of counties in Florida provided motivation for the construction of secondary treatment plants, some of which are high-rate filters and vacuum filtration of digested sludge. Torgerson (4434) described the facilities built to keep up with population growth of Brigham City, Utah. With future expansion in mind, the Charlotte, North Carolina, plant was built in two stages: first stage had biological filtration and the construction connections provided for the second stage (4295). Efforts by the Government to provide new waste treatment facilities for new installations and to update existing installations were published, e.g., Whitesands Missile Range (5627) and Pearl Harbor (4079). Complete waste treatment efforts were intensified as reflected in the literature by Linke (2722) and others (5644) to meet more rigid effluent standards. Increasing waste treatment capacity was reported by Smith and Wittenmyer (4086) as being aggressively sought, using established and new techniques such as plastic medium oxidation towers. Several areas in this country, such as Rockingham, North Carolina (4707), and overseas at Huddersfield and Winsford, England (1512, 5551), found it economical to construct regional waste treatment facilities using conservative designs of standard percolating filter waste treatment plants. Construction activities in Johannesburg, South Africa (4991), Sweden (5612), India (3310), Canada (642), France (4352), and Great Britain (5286) were indicative of the intensified world-wide interest in pollution control. Many of the waste treatment facilities that were constructed overseas were built along the lines of extending primary plants to secondary plants and correcting an inefficient process which had been operating for several years (5277).

Critique

Papers on the construction and description of new or modified waste treatment plants were published extensively, and it appears that there were three to five papers written for each facility built. These pages were informative, but the value of their volume in the literature was questionable. It would appear that authors should use more discretion in titling and summarizing their work. Several times titles and abstracts gave the impression that the "ultimate in waste treatment" had just been constructed. Upon review of the paper it was noted that it was a typical construction-operation report. Quite often construction elements were reported as being used with little or no justification. The cost of construction was included less frequently in the current literature. Construction trends in the decades demonstrated continued interest in biological trickling filters, with intermittent challenges from other processes.

PACKAGE PLANTS AND PREFABRICATED INSTALLATIONS

Early in the twentieth century, Meckel (2950) and Gerhard (1458) reported the need for wastewater treatment facilities which could handle waste flows from small or remote communities efficiently and without much operational attention. Several papers were issued on the problem of sewage treatment for individual houses (5614), and waste treatment systems for rural areas and institutions were described by Hopkins (2023) and by Berry (291). Standards were developed by the British Standards Institution (4952) for 300 people and by Germany as reported by Antze (84). The principles of design and construction were outlined for small domestic installation treatment facilities by the Ministry of Housing and Local Government (5189). Pettet and Jones (3350) found that by using some of the recommended standard procedures, under certain circumstances, additional treatment schemes were required, e.g., percolating filters following septic tank installations. Faulkner (1246), Sharp (3970), Rogers (3662), and Stephenson (4209) reported on various aspects of design and construction of small waste treatment facilities (populations of 300 or less or remote locations) and described the installations. These were composed of pumping and screening, sedimentation, biological filtration and/or extended aeration processes, sludge handling devices, and the use of package plants.

Package plants have been prepared and installed throughout the world to satisfy various conditions, some of which are described below. Gibson (1467) discussed a package plant comprising a septic tank which encircled a percolating filter and was designed to handle the household wastes of five adults. LaFontaine (2607) described a typical package plant as containing primary sedimentation, aeration, final sedimentation and chlorination of the effluent for the treatment of sewage of small municipalities at low cost. In the development of the Haifa waste treatment plant, several small package plants were constructed in outlying areas of the city in addition to the two-stage, high-rate biological filtration plant located centrally, according to Goldstein (1496). In the development of their waste treatment system, the Auckland Metropolitan Drainage Board constructed and evaluated package plants to serve small communities (4004, 4924). Illustrated descriptions were given of various package sewage treatment plants which were available in capacities from 1,000 to 125,000 gallons per day by Public Works Magazine (5413). The design and operation of the two-stage biological filtration unit packages to serve populations from 50 to 500, have been described (5118, 5414, 5641). The construction of the package plant has been quite often around some central element, such as that reported by Crawley and Brouillette (815), in which a plastic media trickling filter was used. Package waste treatment plants have also been constructed to serve as temporary treatment until permanent works could be built (5113). They have also been used (4514) as the next step in the development on to extremely simple treatment plants, such as lagoons or seepage pits. During the construction of small communities in Florida (2475), package plants were used, and the sewage from a population of 400 was handled quickly and efficiently on an estate in the Netherlands (3688) by this method. Using the package plant concept, Ingram and coworkers (2228) investigated several conventional systems to handle the waste treatment problems in space capsules, but found the results were not as satisfactory as distillation. Many patents have been issued on package plant designs, e.g., to Gilbert (1470), Dannebaum (866), L. von Roll A. G. (3678), Knapp et al. (2514), Mead Corporation (2944), and Schreiber (3897), to name just a few.

Critique

Package plants have been used with various degrees of success. Unfortunate experiences and optimistic advertisements have damaged the credibility of this concept. For the solution of a waste treatment problem at a remote location handling a relatively small flow, package plants are extremely valuable. Temporary treatment systems during construction, expansion or seasonal operations have also used package plants. The various plants available were designed for specific purposes and were constructed to operate with little maintenance. However, to intentionally design a system and not specify procedures for some form of maintenance is a practice that may be more oriented to marketing than results. Papers on the construction of package plants were complete and usually based upon justifiable claims.

MATERIALS OF CONSTRUCTION FOR TRICKLING FILTERS

Most of the reports on trickling filters in the literature have dealt with the process modification and operation. However, of equal significance are the materials of construction, which have also generated a considerable quantity of publications. Calvert (593) described the advantages of some of the electrically driven equipment and construction materials, such as precast concrete, to be used for waste treatment applications. Corrosion of distributors and other components was a problem, as noted by Schaetzle (3853), and an alternative was offered by Lux and Brady (2797) by a greater use of plastic materials in equipment for the treatment and disposal of corrosive waste waters. Quite often the materials used in sanitary works were described in detail, e.g., the book by Blake (348). Escritt published several papers (1201, 1206, 1209) dealing with various aspects of the construction of biological trickling filters, e.g., the type of medium, the construction of underdrains and walls, the construction of fixed and rotating distributors, and the shape and methods of drainage of trickling filters. In an effort to discourage corrosion and deterioration of waste treatment plants, Browne (504) studied the effectiveness of various paints to inhibit deterioration. Experiments have been carried out in Great Britain by Lea and Bessey (2656) to determine the extent of cement deterioration at waste plants, treating dairy waste waters, and it was found that deterioration of Portland cement mortars was influenced by the temperature of the effluent. The most severe cases occurred (2656) in storage and holding tanks and partial protection was obtained by using tar or bitumen based paints. The only completely satisfactory results were obtained from untreated, high alumina cement. The structural details of walls, floors, drainage channels and ventilation systems were described by Rankin et al. (3501) and the "Handbook of Trickling Filter Design" (5574).

Distribution

The significance of distribution of waste water over the trickling filter was recognized by Simpson (4035), Eliassen (1152), Chase (656), and others. For proper distribution and intensity of the waste water falling on the medium, flows were adjusted (4035) to avoid stripping the biofilm so that some larvae remain in the filter to aid in checking excessive growth of the film and control filter fly breeding. Milk wastes, when treated on biological trickling filters packed with small grain material, did not respond to any particular method of distribution (5373). Hewitt (1927) reported that rotary distributors constructed with a main arm and an auxiliary arm operated much better with the auxiliary arm continually working. Spray jet distributors were reported by

Merciot (2974) to increase the aeration of sewage, but their installation and upkeep were costly. Maier and Sohler (2830) in 1929 used several types of distributors, such as traveling, scattering and rotary sprinklers, with respective cost information. Several distributor arrangements were noted by Baxter (224), e.g., the Salmesbury distributor consisting of corrugated metal sheets with staggered outlets.

While using spray distribution, various workers, such as Watson (4633) and O'Shaughnessy (3257), modified nozzle design. Spray nozzles which delivered sewage a distance of 9 feet raised the dissolved oxygen 50% or to about 6 ppm, according to Anderson (80). Watson (4628) disagreed and stated that better distribution caused by movable distributors is not worth the increased cost over that of fixed sprays and that the difference in efficiency was hardly noticeable. Watson (4630) recommended that fixed sprinklers be used working under a head of from 5 to 6 feet. Wilson (4762) cited the advantages of aluminum and its corrosion resistant alloys for use in sewage works construction. Tests illustrated that aluminum and its alloys were almost unaffected by the exposure to average domestic or combined domestic and industrial sewage and were a desirable material for trickling filter distributors, as well as other appurtenances. Information dealing with noncorrodible material for sewage construction was published, and it suggested that a wider use of steel substitutes such as Armco and Tonco iron, monel metal, copper bearing steel, tin, nickel, brass, noncorrodible irons and steels and aluminum should be used in wastewater treatment plants. It was stated that aluminum alloys had been able to withstand immersion in sewage for 360 days at Cleveland, Ohio, without detectable deterioration (5370).

Several devices were constructed to distribute the sewage, such as the Fiddian rotary machines (958, 5458). Other distributor arrangements involved the flow of sewage downward from pipes above the beds in vertical jets which impinged upon cup-shaped splash plates (5130), channeling in the medium (5125), water wheels (2844), automatically controlled traveling distributors on rectangular beds (5051), and injecting controlled quantities of sewage at various levels into an air gap medium (2222). Sufficient disagreement on the optimum distributor was generated that Saylor (3841) evaluated the relative efficiency of several of the sprinkling devices and found nozzles to be very satisfactory. Devices described by Ippolito (2231) which used spraying paddles on rotating distributors were reported to perform better than rotating distributors with simply bored arms. The Candy-Whittaker patent (1173) for a rotary sprinkler device was one of the earliest patents for distributors. Patents were issued on many of the distributing devices, for example, Bolton (396), Bohman and Nettermann (386), Geiger (1446), and Hoffmann (1976). The quantity of patents on distribution systems has necessitated a section on patents, which is given later in this review.

Critique

Several materials were used in many designs for distribution of waste waters on biological trickling filters. The results of several investigations indicated that aluminum rotary distributors were well suited to handle waste waters for many years without corrosion problems. The volume of literature was indicative of the many problems which have arisen in the development of distribution devices, and the economic potentiality of providing this equipment. Problems with corrosion were common in the plants built in the 1920's and 1930's. New alloys became available after World War II, and design and construction trends incorporated them into existing and new installations. Sufficient work was reported on effects of distribution, and manufacturers' claims have been adequately evaluated by the plant operators.

Medium Materials

A wide variety of materials was used for trickling filter media; for review purposes, these materials have been divided generally into the four categories: (1) man-made inorganic, (2) natural inorganic, (3) man-made organic, and (4) natural organic. A critique of the literature on materials of construction for media follows the media evaluation section. The quantity of literature available on the various media types, tests, and operational advantages and disadvantages requires review of selected articles with heavy referral to additional references. A high percentage of the literature was concerned with the comparison of one medium versus another for a given waste and set of circumstances (which is summarized at the end of this section), information on specific media (which follows), and development of procedures for medium durability testing, for instance, the British Standards Institute (4951), Payrow (3314), and Kreige (2566).

Man-Made Inorganic Media

Under the category of man-made inorganic media, materials such as asbestos, brick, clinker, metal, lime-treated peat, various slag materials, and various tile or ceramic forms are included. Asbestos material was used by Eckenfelder (1082) and Zigerli (4865) as a medium for biological trickling filtration. Metal was used as trickling filter media in the form of copper-mine waste rock by Horasawa (2030), empty condensed milk cans by Trebler et al. (4444), rotating metal disks by Hartmann (1772) and plastic impregnated metal or paper by Sullins and Self (4265).

A tremendous amount of literature (more than 100 reports) is available on the use of clinker, i.e., the solidified products from a combustion process, as a medium for biological trickling filtration. The literature indicates (1241, 5421) that clinkers for trickling filter media have been used since the early 1900's and are being used contemporarily (4428, 4463) to evaluate other types of medium, waste to be treated, and efficiency of removal of waste and bacteria.

Cotton finishing waste (384, 5616), paper waste (1394), and chemical waste (1573) are just a few of the many examples which are reported as being treated using clinker-filled biological trickling filters. Patents, such as that assigned to Arnatt and Hopper (90), using clinkers in various configurations for biological trickling filtration were issued. It is interesting to note that research was done at the Hamburg Hygienic Institute on clinker-filled trickling filters to prove that they were biological reactors, thus disproving the so-called Travis theory that the purification process is not the result of biological activity (5124).

Another source of man-made inorganic medium has been referred to as boiler slag (3664), gas plant slag (2998), and blast furnace slag (4854). The wide acceptance and usage of slag as a trickling filter medium were based on soundness tests such as those reported by Kreige (2566), and Payrow (3314) to demonstrate the durability of the material. Hommon (1995) recommended that the specifications for slag to be used in trickling filters are: slag should pass the sodium sulfate durability test at 20 cycles, metallic iron should be removed, the gradation should be such that 95% of the material is between 1.25 to 2.5 inches or 2.5 to 3.5 inches as required, and placement of the material should avoid breakage and segregation. Organizations, such as the British Slag Federation (4950) and the National Slag Association (1993), as well as the British Coke Research Association (4947), investigated and promoted the use of slag for various purposes, one of which was its use as a biological trickling filter medium. A patent was issued to Thomas (4362) in which sewage was passed upward through a loose bed of granular material, such as cellular slag, for colloidal and organic removal, and Rudolfs (3738) described a typical slag-filled filtration operation . Solin and Erlebach (4103) demonstrated that slag had a sorptive property for the removal of mono- and divalent phenols. Erlebach et al. (1188) reported that removal of fatty acids from waste waters by slag was analogous to the phenol removal. Sorption of cresols on slag was reported by the same group (4106), with the process of sorption and resting described to occur on a seven- and two-day basis. Madera and coworkers (2816) reported on the successful use of slag, taking advantage of sorptive capacities as well as biological growth. A variety of aqueous solutions was used, e.g., monovalent and polyvalent phenols, cyanides, trinitrotoluene and synthetic detergents or industrial waste containing some of these substances. A waste slag obtained from the manufacture of phosphorus was reported by Fromke (1363) to contain less solids, had a higher pH value than boiler slag, and would accumulate less sludge. The Water Pollution Research Laboratory (5193) has, for many years, investigated various aspects of the use of slag as a biological trickling filter medium. Waste waters from the fermentation process were reported by Pitts (3390) to have caused some disintegration of blast furnace slag used as a filter medium. Sima (4030) described the operation of slag filters in Prague and stated that slag medium was better than limestone for the given hydraulic and organic loadings. Size effects of slag were reported by Oliver and Hall (3241); slag in sizes smaller than two inches produced effluents of higher quality, but were subject to considerable amount of ponding. Information may be found in the many additional references dealing with various industrial wastes having been treated on slag as a medium for trickling filters, i.e., biological functions occurring during filtration, various loading rates, waste treatment at various geographic locations, specific operational difficulties, ventilation and temperature effects, and miscellaneous facts.

Ceramic materials such as vitrified clay or brick are another type of inorganic man-made trickling filter media. Goldthorpe and Nixon (1508) have proposed different modifications of tile media, such as the "Huddersfield" tiles, which were described as a tray supported on three legs. As the liquid overflowed from the tray, it was aerated as it was exposed as a thin film on the curved underside of the tile before forming drops which fell into pools on the trays below. Leibee (2673) and Smith and Leibee (4075) reported on the advantages of glazed, vitrified tile for use as a medium. Food processing wastes, high in organic material, were treated satisfactorily on a tile medium which had one-inch diameter holes extending from top to bottom according to King (2492). Raschig rings (designed by H. R. Straight) were compared by Levine et al. to crushed quartzite for the treatment of milk and packing house wastes, with the Raschig rings being superior (2701). Studies by Edwards and Adams (1116) at the Lawrence Experiment Station were made on tiles with one-inch diameter holes and crushed stone. It was observed that the crushed stone had a tendency to clog at high rates but the perforated tile filter did not. Several investigators, e.g., McCulloch (2903), Lubbers (2774), and Hamlin (1697), reported apparent advantages of concrete or unglazed earthenware pipe and tile as a biological filtration medium. The development of many of the ceramic materials resulted in patents being issued, such as to Halvorson (1675), Lewis (2711), and Page (3268). Ceramic materials and clays for trickling filter material medium were used to such an extent that tentative standards for strength determinations were issued in 1945 by the American Society for Testing Materials (4917) and again in 1948 (4918). Many additional references dealing with the various forms of tile media in biological trickling filters for the treatment of domestic and industrial waste under various geographic conditions have been frequently reported.

Natural Inorganic Media

Other media which were used in trickling filters may be classed in a group called natural inorganic materials, which refer to crushed stone which may be basalt, granite, limestone, sandstone, slate, vermiculite or other materials which would be fractured, and various forms of gravel. The popular use of crushed stone for trickling filter media stimulated the report (5436), in 1944, of tentative standards for high rate percolating filters. The recommended size and type of material were stated to be greater than two inches but less than four inches, and could be crushed rock, gravel, or its equivalent, placed in layers to a depth of not less than 6 feet. The use of several mineral aggregates was reported by Kriege (2570) and specifications dealt with the various properties of the media, such as soundness and fracture faces. Stanley (4183), as well as Levine (2706) and Dahlem (854), stressed the importance of the use of a good hard limestone or other material. Small particles and dust should be avoided (4183) and the stone should be rough enough to afford a surface for bacterial film development, but not so rough that the film will not slough off at least twice during the season. Crushed stone has been used by Eaves (1068) in conjunction with other media such as clinker in stratified layers. The stone size ranged from 0.75 inch (1116) to 3 inches (1068). A variety of industrial wastes has been treated by percolating filters using crushed stone medium, e.g., Munteanu (3124) described the treatment of waste waters from cellulose and viscose plants using this medium.

The Dunbar filter, used in the sewage treatment plant at Tempe, Arizona, was a modified trickling filter which contained 20 inches of three- to six-inch stone, eight inches of 1.5-inch stone and six inches of 0.25-inch gravel with sixteen inches of 0.25- to 0.125-inch sand which provided (858) a mechanical-biological treatment. Many other crushed stone references are recorded in the literature.

Volcanic materials have been used as media very early in sewage treatment history and their popularity was attributed to the satisfactory results for industrial and domestic waste treatment (5458). Wormser (4822) studied the decontamination of radioactive liquids by percolating filters filled with pozzolana and observed that the removal depended largely on sorption of isotopes by the pozzolana bed. Brébion and Huriet (452) reported on physico-chemical and biological purification of waste waters from a pulping process and compared a pozzolana percolating filter to a partition apparatus, favoring the percolating filter. Whinstone (another form of volcanic material) was reported by Hunter and Cockburn (2100) to be a satisfactory medium. An 18-foot deep bed was designed using a gradation of from 0.75-inch to 3-inch material. Successful uses of various basaltic forms were reported (630, 3870, 4163, 4285, 4537, 5127, 5458); the results show that these forms are a desirable medium capable of handling strong European domestic waste, industrial waste, waste in remote locations, and to minimize nuisance problems during operation. Demoll et al. (928) investigated the use of lava filter beds and concluded that they have the ability to retain waste for extended periods, thereby providing the best structure for rapid and complete colonization of purifying organisms. Blunk (367) investigated detention times and growth of organisms on lava slack media and determined the relative detention time and the biofilm distribution to be quite promising. Munteanu and coworkers (3125) studied percolating filters containing basalt and crushed stone. The basalt of the same particle size as the crushed stone and under identical operating conditions had an oxidation capacity of 5 to 6 times greater than the crushed stone (4000 grams of oxygen per cubic meter per day in the summer as compared to 750 for the stone). Since there were abundant deposits of volcanic basalt slag in Romania, Murgoci et al. (3132) used high-rate tower percolating filters with basalt medium (30 to 50 millimeters nominal was more efficient than 20 to 30 millimeters) and stated that the filters were easily adaptable to the several wastes treated. Typical of the patents issued was that to Blunk (370), where a filter medium of granulated lava was described.

Granite is another form of crushed material which has been used quite extensively for a medium, according to Halverson (1667). In 1928, an examination of trickling plants (4525) showed that about one-third of the plants suffered from disintegration of trickling filter medium and clogging; however, granite, trap rock, quartzite, and gravel have proved satisfactory, if the material had a minimum size of not less than one inch. During the reconstruction of several plants (429, 3530), the existing medium was replaced by granite or quartzite medium. Fractured face material, such as broken granite, 2 to 3.5 inches in size, was used by White (4705) to provide a large area of contact and ample space for ventilation. In a plant which was engineered for flexible operation, 8-foot deep quartzite medium (graded from 2.5 to 3 inches) was used with and without forced ventilation to satisfy the quality requirements at Webster City, Iowa (5034). Industrial wastes, such as the creamery, packing house, tannery, and rubber wastes reported by Levine (2699), Veeraraghavan and Hariharan (4528), and Molesworth (3055), were treated on granite media in a trickling filter with only minimal difficulties. Many examples of the application of crushed granite as a medium have been published.

Limestone is another example of a crushed inorganic material which was successfully used as a trickling filter medium.

A motivating factor in the use of limestone as a medium was the local availability of material which would satisfy the hardness, toughness, and wear required for long-term operation (3686, 5407). The physical strength of the limestone created much discussion and resulted in the development of testing procedures to determine its resistance to abrasion, freeze-thaw, and other mechanical failures, as described by Schaetzle (3849), Lamar (2609), and Wukasch and Bloodgood (4834). Limestone has been preferred over other materials by Harrison (1751) and Maier (2832), and examples of operation under ice conditions (167) have indicated its desirability. Mohlman (3045) used dolomite limestone (2 to 3.5 inches diameter) as an experimental high-rate trickling filter for the sanitary district of Chicago during developmental investigations in 1935. Limestone trickling filters have been reported by Logan (2753), Meyeren et al. (2989), and Wisner and Pearse (4795) to handle satisfactorily a variety of difficult wastes, such as dairy food processing and meat packing wastes. In treating waste from malting and brewing installations, Oliver and Walker (3239) used local limestone as the filter medium to help stabilize the possibility of acidic waste waters, but it was found that, as erosion occurred, the pieces of limestone tended to knit together, thereby reducing the available surface area.

The use of sandstone has been reported by Humphrey (2087), Mars (2865), and Grace (1529) to have some advantages at small installations. Others (244, 1529, 4050, 4979) have used sandstone medium in conjunction with other trickling filter media where the sandstone chips were usually of a coarser size (1 to 4 inches) for adequate ventilation (1529). Slate was used in biological filtration processes by Clark and Gage (693) and others (5074) for contact beds. Slate beds were more often used in sludge handling (5454) and on the Dibdin slate beds (1323, 3220, 4771) which were used to trap colloidal material (5454). Other references to slate medium providing satisfactory treatment were reported by Dibdin (944, 945). Coral was reported by Molesworth in the book, "Waste Treatment," (2238) to have been used for trickling filter operations. In 1929, eight coral trickling filters handled half of the secondary sewage treatment from the city of Singapore (5087). Similarly, in 1932 Buchler (519) stated that Singapore's sewage treatment system consisted of 55 coral filter beds, each 100 feet in diameter, and satisfactory effluent was being obtained. Vermiculite was a suitable filtering medium for biological treatment of cyanide waste waters from automotive manufacturing installations (462).

A great deal of literature has been published on the use of gravel as a filter medium, beginning with that by the Lawrence

Experiment Station in 1908 (691) in which biological treatment was investigated. Gravel (1.5 to 2.5 inches) was reported by Steel and Zeller (4198) to produce an effluent equal in quality to that produced by crushed stone of the same size. In a later study by Steel and Zeller (4197), comparing crushed limestone and gravel, the limestone deteriorated after three cycles of the sodium sulfate test, whereas the gravel was able to withstand more than 20 cycles. Thompson (4374) reported that percolating filters filled with water-worn gravel (1 to 3 inches in size) would have a smooth surface and would result in a shorter period of contact than rougher media, but suspended material would pass through more easily, minimizing ponding. The properties of chert gravel were investigated by Lamar (2610). The results were not optimistic because the gravel fractured and undesirable algae growths developed. Furman (1384) stated that local limestone and river gravel were both satisfactory for Florida operations. In investigating the ecology of gravel trickling filters, Weninger (4677) observed that the biological population fluctuated throughout the gravel material as the seasons changed. Hydraulic investigations of gravel percolating filters were made by Thompson (4373) on high-rate dosing applications. Gravel was used in combination with other materials (165, 1031, 5468) in mechanical-biological filtration systems. Objections to the use of gravel were made by Herring (1898), who showed that 1.5-inch size gravel had only about one-half the specific surface area possessed by an equal volume of slag. Clinker was reported to give better results than crushed gravel for the treatment of combined trade waste and domestic sewage in Great Britain (1573). The many combined uses of gravel and its common availability throughout the world generated a large quantity of reports on its successful application and problems in usage.

Natural Organic Media

Another broad category of material which has been used for trickling filter media may be considered as naturally occurring organic material. This type of media includes wood in various forms, organic deposits such as peat, soft coal, hard coal, and other ingenious uses of available materials. Wooden lath was used (5113) as a medium for trickling filters; an advantage was the light weight which was appreciated for portability. Kimball and Wadhams (2482), while investigating methods of treating industrial waste, determined that a trickling filter composed of layers of lath lattice work would handle the wastes which were discharged from distilleries, breweries, and dairies to produce a 90% purification without clogging. Levine and coworkers at Iowa State College (2691, 2692, 2693, 2696, 5231) used a lath filter for a series of investigations on the biological purification of a dairy waste and were able to obtain satisfactory effluent quality.

Steel and Zeller (4196, 4858) have used a lath filter for the treatment of dairy waste with similar successful results. Kennedy (2430) used a lath filter following an aeration unit to handle a creamery waste with domestic sewage. Food processing waste was reported by Kimberley (2484), in 1927, to be treated on lath at the rate of 2 million gallons/acre/day (46 gal./ft^2/day). Middlebrooks (2991) used a random wood stack in handling high temperature waste from paper processing as an effective complementary treatment to plastic media trickling filters. Distillery wastes were treated according to Hoover and Burr (2021) to 90% removal on lath trickling filters when a load of 2,000 mg/l BOD was applied at a rate not exceeding 1 mgad (23 gal./ft^2/day). Lath was used by Sander (3820) to treat compressed yeast factory waste waters and, with proper dilution of 1:3 to stabilize the pH, good results were obtained. Wooden slats were also used in combination with other materials such as coke, as revealed by Biczysko (321), for treating phenolic waste waters in a high temperature biological oxidation system.

Other examples of naturally occurring organic materials used for trickling filter medium were brush branches, twigs and straw. Imhoff (2168) and Thackwell (4347) reported the economical use of brush wood as a medium for contact aerators for certain conditions such as partial purification. Prior to 1930, brush wood was often used (3148, 5366) instead of stone for percolating filters at loading rates of 2.75 mgad (62 gal./ft^2/day) and the filters were still operating after three years. Successful operation of brush wood percolating filters was reported by Lloyd-Davies in South Africa (2745), because the flow could be three times that of a broken stone filter, and the stone filters would cost almost four times as much as the brush wood filters. Hamlin described the application of the brush wood filters in South Africa (1687), but Francis (1338) critically remarked that brush wood filters were not as satisfactory as stone filters. Redwood bark was proposed by Carpenter (622) to be used as a medium and it was suggested that the specific surface area was as much as one hundred times greater the specific surface area of conventional media. A residual charge on the redwood fiber was claimed to enhance better colloidal entrapment and development of microbial colonies. Burton (543) proposed redwood bark as a suitable medium for use in percolating filters which could subsequently be used as a soil conditioner and fertilizer. A patent was issued to Girard (1482) in which wood shavings were provided between the dosing siphon and the bacteria bed to provide a higher degree of treatment. Straw filters were used by Richards and Weekes (3587), and the straw with the retained organic solids was an excellent soil builder. The practical application of this process (3587) was limited to sewage works having access to large quantities of straw and where the demand for soil conditioner exceeded the supply.

Peat, either directly or with treatment with lime, is another example of naturally occurring organic material used as a medium. Schlick (3869) measured the relative efficiencies of Iowa peat, corn cobs and other inorganic materials for small plants. Daire (856) and Acklin and Camenisch (11) observed operations using peat for mechanical filtration, as well as biological filtration medium. Industrial wastes were treated satisfactorily by filtration through peat, e.g., dye works (3880), glycerol wastes (4720), and decontamination of cyanide waste (526). An objection to the use of peat was raised by Guth and Keim (1628) because the mechanical stability of peat blocks failed after four months' operation. Slag was much to be preferred, unless the price of peat was exceptionally low. Büttner (570, 571) described a process which involved the use of peat which was treated with powdered limestone. Successful operation (571) which produced an adequately treated effluent plus a source of fertilizer was obtained from a trickling filter with peat media. The upper layer of peat was removed weekly, mixed with fresh sludge and allowed to rot in piles for two to three months. Patents were issued to Maier (2836), Meyer (2986), Acklin (12), and Dickmann (965) on various arrangements using peat as a trickling filter.

Anthracite coal is also an example of material in the category of a naturally occurring organic medium. Turner (4482) stated that the Lawrence Experiment Station was one of the first installations to use anthracite, in 1901, in a filter 12 inches deep. Anthracite filters were used to handle high solids waste water or effluent, (3349, 4482), but Kountz (2556) also used coal as a trickling filter medium. Loadings of 20 mgad (460 gal./ft^2/day) gave a BOD reduction of 40% without recirculation for treating slaughter house waste waters. Mechanical filtration of effluents (3346, 3348, 4243, 5488) utilized an anthracite medium, the loading rates of which were 200 to 300 gal./ft^2/hr. Clifford (717) indicated that liquid contact time of coal versus gravel medium trickling filters favored the longer detention time of the coal medium, but little significant removal difference was demonstrated. The sewage experience of the city of Bradford, Great Britain, which was reported over many years (244, 4978, 4979, 4980, 4981, 5300) indicated that the coal medium trickling filters, which had been built and operated for many years, had developed serious operational problems due to plugging and that stone medium, graded gravel and other inorganics would replace the coal.

Man-Made Organic Media

Plastics for trickling filter media are another area where materials can be classified into a fourth category, that of organic material developed by man. Plastics such as polyvinyl chloride (98, 643, 678, 815, 1876, 2230, 3025, 4965, 4970), polystyrene (513, 514, 1772, 4970, 5184, 5193, 5324), and polypropylene (4970), as well as others, have been proposed and used in the treatment of industrial and domestic waste waters.

British investigators, e.g., Isaac (2240), Pearson (3328), and Chipperfield (677), have reported on the advantages of using plastic media biological trickling filters relative to other media in waste treatment processes. Smith and Leibee (4074) suggested the use of plastic media as a superior alternative to commercial grade rock to provide more specific surface area, yet still allow adequate ventilation void space. Some of the plastic media were designed to allow the waste water to fall in a thin film (5030), while others have reported designs which create droplets in more turbulent flow (154). Plastic media trickling filters as combination cooling towers and biological units were investigated by Burns and Eckenfelder (538) and found to be only slightly desirable. While handling wastes which were characterized as having the tendency to plug normal biological filters, Brown (492) suggested the possibility of improving the ventilation of the filters by using a plastic medium. Egan and Sandlin (1120) loaded plastic filter media up to 750 pounds of BOD per 1,000 cubic feet per day and removed up to 350 pounds per 1,000 cubic feet per day by this treatment. Berridge and Brendish (286) examined the successful use of plastic media for handling digester supernatant.

The development of new plastic media for trickling filters generated additional information on design (2955). The increasing popularity of the use of plastic media for industrial waste applications was indicated by recent publications of an annual review (4948) and book (308), and Sak (3811) reported further experimentation to be underway. Biological industrial waste treatment using plastic media trickling filters was reported by Lux and Brady (2797) and Stack et al. (4158) to be an intelligent use of the material where a waste provides a difficult sloughing biological film or where waste waters are particularly corrosive.

Industrial waste applications of plastic media have been heavily reported, e.g., pulp and paper mill effluent treatment (488, 643, 1009, 1082, 1083, 1449, 3795, 3812, 4574, 4970), effluent from coke ovens, steel mills, and metal processing (1936, 3437, 3489), for handling detergent wastes (815), for handling textile mill effluent (326, 678, 681, 3124, 3808, 3812, 4094), for the treatment of oil and petrochemical plant effluent (516, 1331, 1332, 1740, 2941, 3968), effluent treatment from food processing plants (643, 983, 2972, 3812, 5324), treatment of meat processing plant effluent (1417), brewing and distillery effluent treatment (678, 681), and treatment of dairy effluents (1157). The various loading conditions and advantages and disadvantages of these media for the industrial waste applications will be reviewed separately under the specific waste in question. The great world-wide activity in the development of the plastic biological filtration media was indicated by the patents which were issued, e.g., Japan (4342), Belgium (2216), Austria (3481), and Britain (2215). U. S. patents were issued to several individuals and companies, such as Porter and Kohl (3438), Hall (1661), Quinn and Franzoso (3495), Sullins and Self (4265), and Fry (1364).

Another form of organic material which has been developed by man to be used as a medium for biological trickling filtration is coke. Coke was used by Matthes (2887), Clark and Gage (693), and Pollock (3403) as a percolating filter medium, early in the 1900's and before, and as a mechanical-biological filter. Loading rates were reported at 10 mgad (230 gal./ft^2/day) on a 24-inch deep filter (3403), and 50 to 70 gallons per cubic yard per day (2666, 5476) for deeper coke medium filters. Biological filtration using coke filters was described by McCracken (2902) for the development of a waste treatment facility involved in the water supply at Amesbury, Massachusetts. Coke was used in novel applications such as the sectioned filter described by DeMoll and Liebmann (927). Ten-centimeter deep coke granules (3 cm in diameter) were spaced apart by 10 centimeters and produced an acceptable degree of treatment. Coke used in combination with other materials, such as clinker, was used by Snook (4092) to aid in the development of a nonplugging percolating filter. Goldthorpe and Nixon (1508) compared coke to a newly developed tile medium, but the effluent from the tile, even though it had a longer detention time, was still inferior to the coke effluent.

Many industrial wastes have been treated using coke as a trickling filter medium, e.g., agricultural industry effluents (971), dairy and milk product factories (5168), phenolic and high BOD waste from chemical plants (1393, 2583), textile and tannery waste disposal (2105, 5565), ammunition plant waste (4730), and brewery and distillery waste (3089, 3693, 5057). As with other media developed by man's ingenuity, there were several patents issued, such as to Mars (2864, 2865, 2866) and to Duval (1052).

Additional materials and different shapes of previously reviewed materials have been used for trickling filter media. Paper, waterproofed by various methods, was used (1611, 3560, 3561, 4265) for biological trickling filters. Phosphate-impregnated asbestos papers for biological trickling filtration were patented by Quinn and Franzoso (3495) to provide added nutrient benefit during the growth of biological organism. Different shapes and configurations of the medium, such as disks, were used in laboratory and field operations (355, 926, 990, 1621, 1770, 1772, 2350, 2464). A further extension of the work using disks was accomplished by using spheres or inclined planes, either plastic or ceramic or other materials, which were reported to give varying degrees of operating efficiency (31, 100, 154, 364, 781, 2065, 3481, 4042, 5186). Free fall media (clear drop flow pattern) were reported by Demoll and Liebmann (926) to have some advantage. Free fall (926) generally was avoided because contact time between waste and microorganisms was minimum. Honeycomb structures, arranged to allow the waste to trickle downward (513, 3268, 3495, 3560, 3561), had structural stability and adequate ventilating properties. Air gap media were reported as sectional devices whereby the media were suspended in layers one above the other. Multiple layer media were reported by various authors (522, 526, 1031, 3348, 4824) to have advantages on nonplugging and mechanical filtering ability. Screens of various materials and sizes have been used to support biological growth in the laboratory and in the field, e.g., polymer foam with screens by Imperial Chemical Industries (2216), vertically suspended wire screens by Schulze (3914) and by Green and coworkers (1571), and Reinsch-Wurl screens with a mat of anthracite (5100). Quite often the biological trickling filter media were fabricated in the form of sheets (98, 250, 513, 1364, 1661, 3155, 3481, 3890, 4096).

Media were devised, as previously noted, to be constructed in various layers of either different materials, different sizes, or structural configurations.

Media Evaluations

By way of summary, it was of interest to note the investigations which were involved with the comparison of one medium versus another. This type of study was reported extensively in the literature with various conclusions being drawn. Investigators, such as Farmer (1239) and Grant, Fulton and Litton (1534), demonstrated early in this century the awareness of alternative medium testing to provide the most reliable system for biological treatment. Materials such as clinker, gravel, broken pottery, quartzite, granite, and limestone were tested.

The tempo of investigations on media increased during the 1930's and investigators such as Hurley (5210) found that the difference between porous and nonporous materials in filters was evident only for a period of time and then tended to disappear. Lloyd and Mountfort (5210) only partially agreed with Hurley's comments. They considered that good clinker gave better results than coke medium, but that coke had the advantage of uniformity and durability. Gravel was suggested by Miller (3004) as the most economical medium; however, experiments had shown it to be unsuitable for conditions similar to those investigated by the previous three authors.

While investigating the Aero-Filtration system, Halvorson (1667) compared the use of gravel, trap rock, and tile and was able to demonstrate that only with high rates of recirculation could media other than tile be used. Work by Rudolfs et al. (3739) on crushed stone, slag and gravel in various sizes indicated that: (a) the slag retained more solids than the other media, (b) the degree of purification achieved by the two media with similar sizes was about equal, (c) there was a marked difference between the effect of coarse and fine materials (an increase in the BOD load caused a poorer effluent but the percentage reduction was greater), and (d) an increase in temperature appeared to have a similar effect as an increase in surface area. Based on considerable investigation and observation, Stanley (4185) concluded that excessive clogging was involved in the use of clinker, coke and coal. The more durable materials such as crushed trap rock, quartzite and certain granites, as well as crushed slag, when available, and limestone, if it passed the hardness test, were preferred.

Filters constructed from sectional lath, cinder or clinker, quartzite, gravel, ceramic rings, broken tile, and corncobs were studied by Levine and coworkers (2700) for the purification of milk wastes. They observed that: (a) the cinders proved very efficient but clogged after five months' operation; (b) a sectional filter with air gap layers was less effective than a continuous solid filter; (c) the lath filter was inferior to the cinder filter; (d) the ceramic rings produced results inferior to those obtained with gravel; (e) the tile filter was very efficient for reducing BOD, but clogged badly; and (f) the corncob filter gave high removals, but the bed depth shrank 35%. Rudolfs and Chamberlin (3728) investigated crushed stone, slag, gravel, and one-half inch galvanized wire mesh laid at one-half foot intervals. The effectiveness of the medium was measured by the degree of nitrification and the wire filter was about three-quarters as effective as the others. Schaetzle (3855) reported that limestone, slag, and trap rock were equally efficient as trickling filter media, if the size of the pieces of each medium was not less than one inch nominal.

In Great Britain, Hawkes and Jenkins (1820), Wilkinson (4733), and Truesdale et al. (4463) measured the effectiveness of crushed granite, crushed gravel, and river gravel in various sizes, as well as slag and clinker in large scale installations. Data were reported by Truesdale et al. (4463) on different sizes and textures of media with specific surface areas of 28, 32 and 35 ft^2/ft^3. After 12 months' operation no significant difference in BOD removal was observed. The effectiveness of a polystyrene plastic medium was reported for application as a high-rate roughing filter (4463) and was compared with 2.5-inch rounded gravel. The effluent from the plastic medium was about 25% higher than the effluent from the gravel medium, but after six months' operation, the two effluents approached the same strength. The film growth on the surface of the plastic media (4463) never approached the high development exhibited on the rock media.

Investigations by Kalabina et al. (2365) were conducted on quartzite, gravel, limestone, coke, anthracite, and boiler slag. It was shown that the oxidative process took place on all filters at approximately the same rate. There was considerable loss of the biofilm from the limestone, quartzite, and coke filters, which was interpreted as an advantage since plugging would be minimized.

Plastic media were the subject of several investigations, such as by Egan and Sandlin (1120), the Water Pollution Research Laboratory, Great Britain (5193), Chipperfield (678), and Germain (1460). The normal observation was that compared to inorganic media higher hydraulic loads were used (4841) and higher organic loads were effectively removed (1120). Industrial waste applications for plastic media were strongly recommended (678), especially as roughing filters, for which most plastic media have been designed. The Water Pollution Research Laboratory (5196) reported on the various characteristics such as bulk density, specific surface and proportion of voids for commercially available plastic media, as well as conventional two-inch rock (Table 3). It was strongly emphasized (5196) that plastic packings were designed primarily for partial treatment of wastes. High hydraulic and organic loadings could be used on plastics which were not particularly suitable for the treatment of effluents to a high standard. The more conventional random pack media were superior (5196) for establishing high effluent quality.

Critique

After many pages of referenced comments dealing with construction materials used as media for biological trickling filters and a documented summary-evaluation, there is little left to say. Generally speaking, the quality of papers was high and, with the exception of a few, common conclusions may be extrapolated.

It would appear that detention time, i.e., specific surface area, has been given a primary role in determining the efficiency of a biological trickling filter. The significance of the micro-surface characteristic is, at best, only minimal. Media which possess suitable physico-chemical properties, in addition to providing a biosurface, are helpful for wastes which are difficult to degrade. The properties of strength, durability, and chemical inertness are commonly accepted and required by all investigators, except those wishing to use the medium for subsequent purposes.

Table 3

Characteristics of Types of Filter Media (5196)

Composition of Medium	Bulk Density		Specific Surface		Proportion of Voids, %
	kg/m^3	lb/ft^3	m^2/m^3	ft^2/ft^3	
Polystyrene sheets	64	4	82	25	94
Polystyrene sheets (close-packed)	48	3	187	56	94
Polyvinyl chloride sheets	37	2-3	85	26	98
Polyvinyl chloride tubes	80	5	220	66	94
Rock, 2 in. diameter	1350	85	105	31.5	ca 50

Based on this review, it seems evident that a wide variety of material can be used as the support and have satisfactory performance, provided the guides for design of an ideal medium are sought. The basis of choice of a medium should be economics and an evaluation of the properties of the types available.

Materials for Underdrains

Information dealing with the design, construction, and materials for the underdrainage of biological trickling filters has been reported in a series of articles by the Public Works Journal (3501, 5378, 5382), by the Trickling Filter Floor Institute (5574), by Mahlie (2824), Escritt (1191), and others (1201). Underdrainage systems (5382) must support the medium and the drains be designed so that there is an uninterrupted straight line following the floor slope to a central drain. Dickinson (958) and Watson (4630) recommended the use of tile underdrains laid on an impervious floor (concrete) with open joints between the tile. Mieder (2994) reported on a situation where a filter with no underdrainage system, other than large stones, had crumbled; the floor levels were very uneven, creating an undesirable drainage-ventilation situation. A large number of reports were published on the use of specially designed tiles for underdrain systems, which were carefully placed to provide the desired drainage (426, 1529, 3804, 4015, 4628, 5458). Inverted channels in the concrete floor were reported (5125) to be arranged in parallel rows connected with larger channels at right angles to provide adequate drainage for large trickling filter beds. Reinforced concrete was used by Walker et al. (4579) to provide underdrains and a floor for an experimental trickling filter in Pennsylvania. Underdrainage systems of vitrified paving brick were constructed by Wagner (4568) and were quite similar to previous references of various forms of tile underdrains. Another example of tile usage was that noted by Rhode (3582) in which the filter was underdrained with perforated clay pipes. Small purification plants for household drainage were described by Hepburn and Drosten (1888). They suggested that the filters be constructed of timber and inserted in excavations of porous dune limestone. Chipperfield (678) noted that with the development of lightweight plastic media heavy supporting underdrain structures would not be required. The Handbook of Trickling Filter Design, sponsored by the Trickling Filter Floor Institute in cooperation with Public Works Magazine, illustrated the use of various types and the specifications of tile underdrain systems, such as that outlined by the American Society of Testing Materials, Section C, No. 159 (5574). Typical of the many patents issued were those to Whitacre (4702), Barbour (169, 170), and Levine (2694) for modified underdrain systems.

Critique

Supporting structures made of strong durable materials were reported. Little conflicting evidence was offered on materials of construction. Designs included the concept of rapid drainage, high ventilation, media placement on the drains, and other factors of construction. Only slight mention was noted of underdrain systems and materials being designed with cleaning ease in mind. The development of lightweight media has placed materials such as noncorrodible metal gratings and others into an area previously occupied by inorganic clay types. It would not be surprising to see, in the future, other lightweight, economical materials used to provide the support, effluent transport, and ventilation required for the operation of biological trickling filters.

Materials Used For Construction of Enclosing Walls and Architecture

The design and material selection for the construction of walls of percolating filters were described by Stockley (4221) as a matter of some concern. Reinforced concrete was commonly used with the walls being designed as ring tension units.

Frequent failure of these walls was explained by Bergman (278) as being due to the daily fluctuation in temperature which caused expansion during the day and contraction at night. Investigators such as Modersohn (3033) have been proponents of perforated walls surrounding the medium to provide better aeration and removal of carbon dioxide. Percolating filters constructed after 1960 for the City of Bradford, Great Britain, took advantage of thin, impervious plastic membrane placed on earth-fill excavation with the stone trickling filter medium placed over the membrane. Kratz (2564) is one of several investigators who reported on the use of rubble masonry as a perforated wall surrounding the trickling filter medium. Reinforced concrete can be used (5129) economically for the walls for trickling filters because other unit operations in the plant require this design. Steel has been used (3020) as a containment material for biological trickling filters and advantages in economy and speed of construction were discussed. Jenks (2312) used corrugated metal walls instead of the more usual concrete walls on the Biofilters constructed at San Mateo and other locations in California. Prefabricated storage steel walls were used (5642) for constructing containments for percolating filters with advantages of economy and speed of construction.

Architectural considerations were discussed by Mueller-Neuhaus during the design and construction of trickling filters (3110). As stated previously under the section on enclosures, the architecture was considered (5645) in developing the total trickling filter system. In preparing design standards, Maddocks (2811) suggested in 1940 the importance of architectural considerations in the design and construction of waste treatment facilities.

Critique

The determining factor in selecting a material for wall containment is mainly economic. Walls were used to provide a tank for the filter which could be flooded for the control of filter flies (Psychoda). However, media have been developed upon which flies are controlled by hydraulic loading and other factors. This control removes the limitations of materials for construction, such as metal, plastic, wood and others, from which to build walls. Under the sections on theory and design, the reasons for using walled enclosures were reviewed.

Architecture is an area which obviously can be improved in the design of waste treatment plants in the United States. Plans of plants built in Switzerland usually have definite architectural influence and the total plant appears as one modular unit. Interesting design problems arose when these facilities were expanded while maintaining the original theme. Unfortunately, architectural considerations were not stressed in most of the design or construction reports. With more public attention being directed at waste treatment and its facilities, architectural considerations will undoubtedly be more important.

Materials for Enclosures

Steps to be taken for odor and nuisance control were published in the "Recommended Standards for Sewage Works" (5011). Scharfe (3858) reported on the construction and efficiency of high rate enclosed percolating filters. Descriptions by Lundie (2794) of the use of a Prüss-type filter in South Africa indicated that by forcing air into the top and through the filter impurities in the vapor phase were oxidized in the same manner as those in the liquid phase. Antill (82) described the Prüss-type enclosed trickling filter as being a conical roof with a small fan at the apex for ventilation. Reference was made in this review to the use of totally enclosed sewage works, which indicated that the concept of covering percolating filters was fairly common. Bardwell (172) described an attractive sewage treatment plant at Excelsior, Minnesota, which was totally enclosed to control odors.

Domes have been constructed in Sarasota, Florida, with aluminum panels hinged to aluminum pipes, in the geodesic design, to allow dimensional changes under conditions of loading stress or irregular expansion. The aluminum dome solved the air pollution problem and eliminated the need for preliminary chlorination of the sewage (1478, 5115, 5116). In the early 1930's, papers were published (423, 4316) describing the construction and operation of percolating filters with glass covers. Eight-ounce translucent fiberglas reinforced panels were used for covering tanks at the Whittier's Narrows water reclamation project at Los Angeles (5656). Concrete-covered domes of spirally generated Styrofoam®* over 80 ft in diameter were built in 1966 (5645) to reduce fog discharge problems from filters. Similar 136-ft diameter domes protected the trickling filters at Elmira, New York, as reported by Dunbar in 1969 (1044). Gilde (1472) patented the use of a flexible cover over a trickling filter which was kept at a positive pressure to contain the objectionable odors until the sewage is filtered out by absorption and direct metabolism.

Molke (3056) and Foster (1312) utilized elliptical concrete domes (3.5 to 6 inches thick) to protect the trickling filters from the adverse weather in Hibbing, Minnesota. The literature (3704, 4885) in the late '30's to the mid '40's indicated that the use of enclosed trickling filters was a common feature of sewage plants. Quite often the development of a specialized medium (463, 2350) or issued patents (1212,

---

*Registered trademark of The Dow Chemical Company, Midland, Michigan.

4097) involved the use of various materials specifically for trickling filter covers.

Critique

Covering systems have presented other problems, such as corrosion. New materials should be tried by design engineers in an attempt to solve these problems. A lower cost cover, such as the flexible type, may, however, produce higher operational and maintenance expenses.

SECTION X

OPERATION OF TRICKLING FILTERS

A general description on the operation of waste treatment plants involving biological trickling filters was published in 1942 (5389), and other publications were so similar that a detailed review and listing of these reports would be duplication. Various aspects of operation and operator activities for trickling filters are reviewed in the following subsections.

OPERATION -- KEY TO EFFLUENT QUALITY

Agar has reported (16) the need for proper supervision and operation of sewage works including daily inspection, a record of conditions, immediate remedies for breakdowns, and familiarity of plant personnel with alternative operating procedures. Wisely (4783) charged that it was the foremost responsibility of the plant operator to maintain an efficient and economical operation of the waste treatment plant. Escritt (1194, 1199) stressed the importance of the plant design which would allow flexible operation and intelligent management, e.g., series operated trickling filters which could be operated by alternating double filtration or parallel operation. The operation of small sewage works was considered by Stanbridge (4165) in which he suggested short term, manual labor, low expense items of operation, e.g., control of ponding by forking the surface of percolating filters and by prechlorination of sewage before filtration. Operation of newly designed plastic roughing tower waste treatment plant was discussed by Chipperfield (677).

Operational parameters available for the control of waste treatment plants were emphasized by Malinowski (2850) as dissolved oxygen, settleable and suspended solids, biochemical oxygen demand, degree of nitrification, pH value, and relative stability among others. The influence of laboratory determinations as a means of measuring the effectiveness of the operation of a waste treatment plant was stated to be necessary (4859). Lumb (2780) discussed several analytical techniques useful to the efficient operation of sewage treatment plants. Imhoff (2199) objected to the use of nitrate as the parameter which would indicate a satisfactory effluent and suggested operating trickling filters at a high rate to wash out the accumulated sludge before it has been decomposed. Biological examination was considered by Kalibina (2367) to be a rapid means of judging the quality of operation of a sewage plant. Sima (4029) found that a count of psychrophilic bacteria was one of the most suitable criteria indicating the failure of biological filtration plants.

Typical operational problems such as the accumulation of a fungus on an enclosed percolating filter were discussed by Hunter

Preceding page blank

and Cockburn (2101). Control of the fungus was attempted by inoculating the filter with Achorutes with promising results. Siphons to dose percolating filters to ensure that the distributor arms are not plugged were extensively used throughout the world. Their operation and problems were outlined by Grubb (1607), who noted that overloading of a filter may be due not only to the small size of the filter but also unsatisfactory operation of dosing siphons. A severe challenge for sewage works operation was stated by Killam (2478) to be the combined effect of variations in the rate of flow and the concentration of sewage arriving at different hours of the day. A conservative approach to the design (yet always satisfactory) was to use the maximum concentration as the controlling factor to determine capacities, and during periods of light load the system would be operated as if in a resting phase. A great deal of literature was published on the operational techniques to control filter flies, e.g., Murray (3138), such as diluting the influent, controlling temperature, dosing with chloride or lime, dosing with free chlorine, flooding the filter, enclosing trickling filters, applying salt to the surface of the filter, painting filter walls with oil, flaming the filter stones, and interrupting the flow for seven days. In the discussion of Murray's paper, the degrees of success, advantages and disadvantages of the methods were emphasized.

Many articles were published on the operation of various units, such as contact filters, by Clark and Adams of the Lawrence Experiment Station in Massachusetts (697) in 1914. Operation of Imhoff tanks and contact beds was reported by Fish (1289), indicating the success of the operation on domestic sewage. Operation of dipping contact filters while treating mixtures of sewage in trade waste waters was related by Hartmann (1773). Reports (5648) on the operation of trickling filters by alternating double filtration indicated less trouble with plugging and filter flies. Reichle (3536) compared the operation of two-stage activated sludge and anaerobic treatment with two-stage trickling filter and anaerobic treatment with respect to operation and purification obtained. The popularity of the Biofilter was mentioned in reports on its operation by Lawrence and Eichenauer (2644) and Divet (975). Problems of icing were handled (2644) by recirculating sewage to the secondary filter and operating the primary filter as a low-rate system. Typical of various locations which had operating problems and which were solved were Pontiac, Michigan (3404), a girls' school in Indiana (95), District No. 2 of Hamilton County, Ohio (719), trickling filter plants throughout Illinois (2081), and operation of waste treatment plants at hospitals (1306).

Critique

In most cases, the problems which had developed after a period of operation were corrected by operator ingenuity and resourcefulness with help from other interested individuals such as consulting engineers, regulatory agencies, and others. The operation of today's major metropolitan sewage treatment plant is a large step for operators in a little over fifty years. Fountain (1317) in 1915 reported that the treatment plant serving Calvert, Texas, produced adequate effluent, had no odor 20 feet away, cost $5,000 to build, and required one man 45 minutes a day to operate it. Whereas in 1966, the chemical industry alone has more than 1,700 people working full time and is spending $40 million a year to produce satisfactory effluents, according to Sadow (3809).

OPERATIONAL PROBLEMS WITH START-UP

Operational problems with the start-up of percolating filter systems after reconstruction, flow interruption, or new construction have been reported (3550, 5182, 5422). Beedham (244) outlined the start-up problems generated when several trickling filters were taken out of operation during times of minimum flow and were later restarted which caused the effluent quality to suffer. The solution to this difficulty was recirculation of final effluent, but the cost of pumping would be high. Kleeck (2505) recommended procedures for start-up of new filters. However, biological investigations (4396) indicated that when the operation of a filter was interrupted for seven days the top layer microorganisms were killed, but the deeper layer microorganisms retained their viability. Upon restarting, the efficiency of the filter was expectedly lost, but was reestablished in 10 to 15 days. An operational problem which required considerable skill was acclimating biological processes to treat trade wastes, such as reported by Orford (3247), which enabled a percolating filter to handle the waste waters from a natural gum processing plant. Problems encountered during the initial operation of a plant for the biological treatment of waste waters from the manufacture of pharmaceuticals were published by Pitts (3390), who showed that continuous return of the sludge from final sedimentation tanks to primary aeration tanks aided the operation.

A good example of the type of work on acclimatization was given by Tucker (4477) who investigated two different methods of starting up percolating filters. He concluded that it appeared that a preliminary rapid rate of flow enables filters to reach their maximum efficiency more rapidly than the gradual increase of the rate of flow, and more satisfactory results were obtained if a new filter was seeded with partly purified effluent than if it received settled sewage only. Simons (4033) described start-up difficulties and their elimination in the start-up and initial operation of a percolating filter plant in Orlando, Florida. Treatment of domestic sewage plus trade wastes from a cotton mill generated odors, which were masked by treatment of the incoming sewage with Orthosolv, an emulsifiable chlorobenzene (2688). Freeman (1348) published, as have many authors, the start-up problems which were eventually overcome, in this case at Fayetteville, North Carolina. The acid conditions were prevented by the addition of lime, the pumping equipment and valves controlling the pressure of waste gas were adjusted, and grease balls formed in the crude distribution box were broken up with water.

Critique

Start-up problems have been adequately reported and techniques to solve them evolved due to operator experience and participation in forums and discussions, and most situations are now well understood. Operation data did imply the lack of design and construction considerations for certain common problems in waste treatment plants. However, with improved communication and more qualified operators being available, corrections of these design difficulties are being incorporated into new plant designs.

OPERATOR TRAINING AND RESPONSIBILITIES

Several workers in the sewage treatment field expressed the necessity for formal training for sewage plant operators (1122, 4505). The importance of operator training was recognized (946) early in the history of waste treatment, as W. J. Dibdin stated in 1897 in his book, "The Purification of Sewage and Water."

> "If the work is to be trusted to men ignorant of the first principles of the duty entrusted to them, failure will be directly invited. Hitherto the one great difficulty in the way of success is the persistence of authorities in placing in charge men who, however intelligent, willing, and honest they may be, have not had the training required for that systematic supervision so essential in all operations conducted upon scientific principles. Let those in authority ask themselves, 'What would become of a brewery if entrusted to the management of a man who knew nothing of brewing? or of a foundry, or, in fact, of any ordinary business if placed under the direction of one who knew nothing of the scheme underlying his work?' The remedy is obvious."

In an effort to supply some of the technical information, agencies such as the Iowa State Board of Health (5230) and the New York State Board of Health (3302) published operational rules and guidelines for operators to establish efficient waste treatment plants. As part of the formal training, there has been strong interest (4728) in establishing a suitable licensing law for water and sewage plant operators. The law would provide for the appointment of a competent board of men with recognized experience in the field who would issue licenses to qualified personnel. The board would have the power to force compliance with the law which would establish protection for the public, municipal officials, and competent plant operators.

As an aid to the training of plant operators, manuals were prepared (537, 5337) which dealt with routine instructions for operating sewage works of various types and a variety of information on operation, data gathering, process modification, and safety, along with other assorted information which should be available to a competent operator. The U.S. Corps of Engineers used a model of a biofiltration plant (5109) to train operators for Army sewage treatment plants. Contributions to the field have been made by several workers, such as Cosens (793), to provide basic information and data for operators of sewage works. Methods of measuring flow, concentration and temperature of the sewage, taking samples for analysis and making laboratory determinations were discussed and a description of the sewage plant, including percolating filters, was given. Tomlinson (4412) published a paper dealing with the description of the animal life in percolating filters which was written intentionally to enable the nonspecialist to identify the various forms.

The result of much of this training has been enthusiastic response by the operators, as illustrated by operator forums (5149) in which various operating problems and the solutions of these problems were discussed, providing practical operational methods for the operators. Typical of the operation papers were those submitted by Brooks and Ross (479), and by Booth (404). Organizations such as the Federation of Sewage Works Association and the American Society of Civil Engineers (2392, 5148) have published papers dealing with operating and cost records, annual report writing, routine analysis, supervision levels, operator qualifications, and analytical determinations necessary for controlled operation of waste treatment facilities.

In an effort to continue the education of waste treatment plant operators, an active program of short courses has been offered by several academic institutions. Examples of the academic institutions which had active programs of operator training courses were Louisiana State University (1616, 3632, 4957), the Texas Water and Sewage Works Short School (dating back to 1918) (2893, 2943, 2969, 4347, 4499, 4858, 5568, 5569, 5570), the University of Wisconsin Sewage Works Operators School which began in 1945 (5610, 5611), the North Dakota Water and Sewage Works Conference (2636), the Michigan Sewage Works Operators Association (1142), the Sewage Plant Operators of Pennsylvania Conference (2946), and other organizations overseas, such as the Association of Managers of Sewage Disposal Works in Great Britain (5463).

Critique

The quality of effluent is directly proportional to the quality of operation and the quality of operation reflects the operator training. The trend in favor of more formal operator training has been well established and documented by descriptive papers. The participation of operators in publications and other communications indicates their desire to improve their profession and to establish the waste treatment facility as a point of community or industry pride.

OPERATIONAL COST FACTORS

The review of the literature indicated considerable concern over operational costs of waste treatment facilities. Generally, the initial capital investment for trickling filters has been higher than the initial capital investment for alternative processes, such as activated sludge. However, the operational expenses for trickling filter plants have been much lower than for activated-sludge plants. Several investigators have quoted dollar figures as the cost for treating a million gallons of waste water and brief reference was made to selected publications to give the reader an indication of the magnitude of the cost involved. It should, of course, be kept in mind that for the purpose of comparing actual cost in terms of present-day dollars and under individual circumstances the economics would extend this complex problem beyond the scope of this review.

Examples of operating costs were reported throughout the literature, e.g., that reported in 1910 at Manchester, England (4993). It cost $60,000 per year to operate 20 biological filters and 4 storm water filters plus $42,000 a year for sludge removal. Hoover (2016) stated that the cost for the operation of a conventional treatment plant in 1917 was $1.84 per million gallons. Alford and Burdick (62) calculated the annual operating cost for the Lincoln, Nebraska, waste treatment facility, in 1921, was $12,500, treating 4.5 million gallons per day ($7.60/million gallons of sewage). Streeter (4246) arrived at the operation cost of the sewage plant at Sheffield, England, with a dry weather flow of 18 mgd which was about one-third industrial wastes and a wet weather flow of 65 mgd, to be 18 shillings and 2 pence ($2.10 present day) per million gallons for handling the dry weather flow.

In 1933, Cohn (747) published the operating costs for the Schenectady Imhoff-trickling filter plant handling 8.93 mgd as $8.33/million gallons of sewage, which was 20% less than in 1932. Operational costs on chemical processes were stated in 1934 by Blew (356) to be from $8 to $20/million gallons, exclusive of fixed charges. Rudolfs et al. (3743) remarked on the cost of chemical treatment in percolating filter plants and the cost of chemicals for plain sedimentation (at an experimental waste treatment plant in New York in 1935). The cost for chemicals alone for sedimentation with filtering was $4.30 to $6.70 more than with the filter alone for equal removal of non-settleable solids, from $1.30 to $6.60 more for equal removal of total solids, and from $1.20 to $2.40 more for equal reduction of BOD. The differences in cost increased with the degree of purification obtained.

Also in 1935, Belbin (247) reported operational costs in Scotland to be 177 pounds, 13 shillings and 10 pence (~$4,250) per year to handle the waste from 4,700 people. Kemmler (2426) in 1936 calculated the combined cost for operation, construction, and amortization (4%) over a period of 30 years for four types of plants: (1) Imhoff - trickling filter plant-- $21 to $23 per million gallon of sewage per day; (2) activated sludge plant - $20 to $37; (3) chemical precipitation plant-- $15 to $38; and (4) intermittent sand filtration plant-- $30 to $46 per million gallons per day. Hosegood (2040) also discussed the operating cost of a trickling filter plant in San Bernardino, California, in which chlorination for nuisance control was practiced. For a flow of about 2.9 mgd, the average cost was $10.49 per million gallons of sewage.

Operational costs for a trickling filter plant were stated by Humphrey (2087) for waste treatment at a New York State cannery to be $0.50 per thousand gallons when 50 million gallons of waste waters were treated during 1939 ($500/million gallons). In 1940, Reece (3529) treated dairy wastes on trickling filters with chlorination and lime treatment with the cost of chemicals being $3.70 per million gallons. Babbitt and Bauman (112) published the data obtained by Besselièvre in 1945 which indicated the operational costs listed in Table 4.

Table 4

Treatment Operational Costs of Sewage Plants[a]

Plant Location	Type of Plant	Cost of Operation $/million gal.
Rockville Center, N.Y.	Activated sludge	59.68
Gary, Ind.	Activated sludge	8.79
Galesburg, Ill.	Trickling filter	15.94
Elgin, Ill.	Sedimentation and separate sludge digestion with trickling filters	13.79
Waukegan, Ill.	Chemical precipitation	19.22
Fort Dodge, Iowa	Sedimentation and separate sludge digestion with trickling filters	27.94
Urbana-Champaign, Ill.	Imhoff tank-trickling filter	16.11

[a] Compiled in 1945.

The cost of industrial waste treatment was reported by Hubbard (2075) in England for chemical plant waste waters to be 3 shillings ($0.36) per thousand gallons of crude waste on a treatment system of 100,000 gallons per day. In treating the effluent from pesticide manufacture on an alternating double filtration plant with pretreatment, Sharp and Lambden (3971) estimated the cost at one British pound ($2.40) per thousand gallons including labor.

Another method of reporting costs was used by Smith (4084). The capital cost per pound BOD removed per day, using chemicals and plastic medium treatment, was estimated from $15 to $11.20 for a BOD removal of 2,500 pounds to 20,000 pounds per day, and the power costs (at 1¢ KWhr) for the various units were estimated at 5.2¢/100 lb BOD removed per day for a sewage flow from 0.42 to 5.03 mgd. Kempton and Roskopf (2428) tabulated the costs for a small capital investment which reduced operational costs by taking advantage of local conditions and the requirements of the waste stream to be treated. Relative savings in operation and capital expenditure were calculated by Chipperfield (678), in 1967, for several industrial wastes, but because of commercial interest absolute figures were not published. Several investigators have proposed (5643) various formulas to establish charges based on sewer usage characteristics.

Critique

In review of operational costs, the literature reflected an interesting trend. As the price of waste treatment increased, due to rising costs of labor and material, figures on the cost of treatment per million gallon were not as readily available in the 1960's as they were in the 1930's. Texts, such as those by Babbitt and Baumann (112) and Metcalf and Eddy (2984), made an effort to include cost and economics along with other design criteria. Operational costs are dependent on so many variables that a common basis of comparison is difficult. However, figures such as the cost of the removal of a pound of BOD or of some other pollutional characteristics certainly appear to be a step in the right direction. The descriptive terminology required in developing effluent standards should be made considering the requirements for operational cost accounting. For example, the use of a percent removal figure by a regulatory agency really does not guarantee the receiving body of water sufficient pollution protection. Similarly, the cost per million gallons is on a basis which would allow less expenditure for less treatment. A vote of confidence should be given to the operators of the many waste treatment plants who set the example of getting the greatest degree of treatment for the least cost.

SECTION XI

MAINTENANCE OF BIOLOGICAL TRICKLING FILTERS

Papers such as that by Hamlin (1695) on factors of maintenance of waste treatment plants to achieve efficient operation have been frequently published. During operation orientation, maintenance of equipment is an item that is stressed, as reported in the published literature (5389). The importance of proper maintenance in small sewage works was emphasized by Escritt (1200). Lack of maintenance and the normal wear on equipment have been the cause of reduced efficiency in waste treatment plants (500).

CORROSION PROBLEMS

Concern over corrosion of metal, wood, and concrete structures (504) and serious damage to concrete and pumps (2598) has been expressed by waste treatment plant operators for several years. Much of the corrosion was attributed to hydrogen sulfide (4143), and it was noted that the presence of zinc in copper alloys tended to reduce the corrosion by hydrogen sulfide. The literature (4291) reflected the concern of workers on the operation and maintenance of pumps, electrical equipment, the percolating filters, and other potential trouble spots in the waste treatment facility. Alternative materials such as plastics have been suggested by Lux and Brady (2797) for handling particularly corrosive trade waste waters. Hazlip (1843) described a classic case of corrosion, in Louisiana, where the poor condition of the sewer pipes caused delay in delivering the sewage to the treatment plant, and, consequently, the sewage was frequently septic when it reached the plant, thereby generating nuisance problems and increasing maintenance cost. During the operation of the waste treatment facility, modifications have been incorporated into the maintenance program such as changing the direction of the jets on distributor arms (467, 704). Selection of the trickling filter distributor should be based on low maintenance requirements, as indicated by Baxter (224). Because of the lower required maintenance, traveling distributors were more common in England, in 1924, than fixed nozzles (1807). Quite often the operator was faced with the maintenance of aging equipment, as was the case at the Epsom and Ewell sewage works (4170), but the plant must be operated with the equipment at hand. In rural areas where several small waste treatment facilities were located, Shimnin, in a discussion of a paper by Easdale (1061), advocated the use of roving crews which would have the mobility to maintain several facilities in an effective way. Many examples are available of waste treatment plants which have been operated without proper maintenance (3455, 5077), and then deteriorated in efficiency, effluent quality, and subsequently required additional attention and expenditures.

SYSTEM CLEANING

The cleanliness of the plant has been reported (3800, 5447) to be a primary factor in the reduction of general plant nuisances and operational problems. Procedures, such as outlined by Chase (655), which were no more than simply cleaning tanks every six weeks to four months, are prevalent throughout the literature. Examples of cleaning procedures for the maintenance of biological trickling filter plants are the cleaning of screens (5315), maintaining and cleaning siphon chambers and filter media and distributors (2505, 4951), daily cleaning of multiple nozzles (1781) and maintaining sprinkler filter and feed pipes (3337), as well as many others. Chlorine chemicals, to open clogged pipelines for flow, have been used by Rideal (3602). During operator discussions (2636), methods of cleaning included wire brushing, sand blasting, and sanding. However, it may be cheaper to replace metal parts rather than to keep corrosion under control in the waste treatment atmosphere. Occasional cases were pointed out (5390) where waste treatment unit processes were completely out of balance and it was necessary to flush out the plant before normal operation could be resumed. One method of cleaning a filter medium such as coke, patented by Mars (2866), forced hot gases through the filter, leaving only a coating of fine carbon on the coarse coke. Several papers (1948, 5660) dealt with the removal and cleaning of trickling filter media by screening and washing. Depending on the type of medium and strength of waste, cleaning could be required from every five months for slag (5373) to every five or six years for stone or cinders (2078, 2678).

Biological cleaning methods have been used by Carlson and Cornell (618), which involved an enzyme preparation to clean the nozzles of the filter clogged with grease and to remove grease and scum from walls and other surfaces. Bell (253) recommended the colonization of *Anchorutes viaticus* to keep trickling filters from building thick film layers. Others (1113) have reported on the importance of *Enchytraeid* worms for keeping trickling filters clean during operation.

Several physical methods of relieving clogged sprinkling filters were recorded (5134) as: (a) resting the beds and washing out the dry accumulated matter by normal distribution, (b) washing the filter with water from a fire hose, (c) applying bleaching powder on the surface of the filter, and (d) application of a strong disinfectant or bleach during normal distribution. Many investigators (596, 597, 1949, 2706, 3896, 5131) have used backwash devices for unclogging the trickling filter medium, with and without compressed air, to aid the hydraulic action and with and without mechanical handling of the medium.

IDENTIFICATION OF MAINTENANCE PROBLEMS

In addition to the above information on maintenance, much work was done on identifying maintenance problems at percolating filter plants, such as the effect of synthetic detergents producing foaming and ponding as well as blockage of distributors (783, 4566). Grease from domestic as well as waste waters caused the plugging of the filter medium, blockage of distributors, and reducing the biochemical effectiveness (1887). Procedures which have been used to correct grease build-up have been published, e.g., use of alternating double filtration, high-rate recirculation, inoculation of the medium with an active worm population (1887), cultivating the top six to eight inches of the filter medium (330, 467), the addition of enzymes (789), and other techniques (2825, 4887). Maintenance problems were caused by severe weather conditions (52, 711), and freezing was minimized or eliminated by arrangements of recirculation, raking the surface of the bed, chlorination, and enclosure of the percolating filter.

Percolating filter ponding was discussed many times and was identified, typically, by Lanphear (2628) and Wilkinson (4730). Methods of prevention and cure are well established (5377). Foaming (357, 2386, 2437) produced objectionable conditions and safety hazards, and required additional treatment, e.g., the use of chlorine, antifoam baffles, or design modifications.

A major maintenance item, as indicated by the literature, was the control of filter flies (Psychoda alternata). Kemper (2427) stated that chemicals such as borax, lime, copper sulfate, sulfate of iron, pyrethrum, nicotine, chlorine, and carbon disulfide are useless to kill the larvae and pupae of the fly, since these substances also damage the organisms necessary for the biological treatment of sewage. Other methods were recommended, such as flooding the filter with water, surrounding it with wicker work or green plants, colonizing the filter with Achorutes viaticus, spraying the surface with a mixture of petroleum and pyrethrum, treating the sewage with an emulsion of ortho-dichlorobenzene or of creosote and crude paraffin oil, but each of these has certain disadvantages and is not totally effective. Dekema (914) noted in a patent that nuisance from flies or odors was prevented by adding insecticides, disinfectants, or deodorants with the air stream. To kill the fly in the larva stage was part of the disadvantages of chemical addition noted by Riedmuller (3609) because the Psychoda are necessary in lightly loaded filters for the destruction of solid matter. Gammexane (benzene hexachloride) has been applied (4421) to control the breeding of the filter fly, but it was cautioned that drastic treatment could cause ponding and decrease the efficiency of the filter. A discussion among plant operators (5229) indicated no particular advantage to any one of the suggested procedures for fly control. Hypochlorite was used (4884) to control filter flies. In North Carolina, flies were controlled (2853) by spraying the filters with Malrin and the few adult flies surviving were controlled by a portable fogging machine. Sedimentation tanks were covered with a film of fuel oil to prevent larvae from hatching. A severe problem of active breeding of stable flies (Stomoxys calcitrux L.) arose in Greenville, South Carolina (3170), due to a meat packing waste in high concentration in the influent sewage. Satisfactory control of the fly breeding was established by submerging the filters for 12 hours twice a week. Waller and Ingols (4587) stated that filter flies were controlled in Atlanta, Georgia, by flooding the filters at weekly intervals; however, a serious odor problem was created and chemical addition was required for odor control.

Ponding of biofilters caused by a profuse growth of the sulfur bacterium, Beggiatoa alba, was reported by Shepherd (3989). Flooding the filter with chlorinated water for 48 hours killed the growth. However, flushing out the dead growth was difficult. When the detention time of the flooded filter was long enough to allow anaerobic digestion to occur, the filters were flushed repeatedly, solving the dead growth problem and resuming normal filter operation. Flooding of filters for 24 hours every four days was reported by Rhame (3577) to completely eliminate flies, but seriously impaired removal of BOD. Later reduction of the flooding time to 2-3 hours every four days considerably improved the BOD removal, but did not eliminate the flies. Fuller (1375) completely eliminated filter flies and ponding by flooding the filter 24 hours once a month, and Browne (501) at Marion, Ohio, controlled filter flies by flooding the trickling filters.

Cohn (738) used chlorine to aid in the maintenance of trickling filter plants, e.g., reduce the odors, the biological growth in nozzles and distributing pipes, and the number of Psychoda flies, and increase the amount of suspended and colloidal solids in the effluent. In addition to the above uses, Chamberlin (648) indicated that chlorine was effective in the removal of grease, reduction of BOD, improvement of clarification, foaming, and the control of ponding on percolating filters. Lohmeyer (2755) utilized chlorine to eliminate distributor stoppage due to snails (Physa) which were collecting in the nozzles. Chlorine was very effective in correcting trickling filter ponding, according to Agar (18). Prechlorination of an odoriferous waste (19, 1352, 1896, 4304, 4667, 5060) controlled the release of odors from the trickling filter and the flies, and retarded ponding tendencies. Cohn (743) stated that chlorination did reduce ponding in trickling filters, but was not a very effective agent in controlling filter flies.

NUISANCE CONTROL BY ENCLOSURES

Several general papers (2671, 5497) outlined the advantages of enclosing nuisance-causing unit operations in waste treatment plants. Blunk (372), in reply to criticism of another of his papers, described the effectiveness of nuisance control by enclosure in the late '30's. Pönninger (3407, 3417, 3421) published much work dealing with control of the *Psychoda* fly and odors on enclosed trickling filters in Germany. Pönninger worked with sewages of various concentrations and septicities and developed experience in ventilating enclosed trickling filters. Imhoff (2197) expressed the opinion that, if,through faults in design or operation of the plant,odors cannot be completely controlled by chemical means, then the whole or at least part of the plant may be covered and ventilated, with the air treated with activated carbon or ozone. Not only was there concern for nuisances, but also for safety and the quality of the local waste treatment plant environment. Müller (3119) briefly summarized the toxicity, odor generation and corrosive effect of hydrogen sulfide in sewage treatment works.

The nuisance conditions experienced around treatment plant works may be similar to that published by Planchon (3393) in treating the waste from abattoirs in France. The heavy organic load and the small plant usually available dictated that it was best treated on a closed aerated percolating filter to diminish odor and fly nuisance. Likewise, others have reported (1618, 1700, 5250) from the early 1900's to the present that enclosure of the percolating filters and forced ventilation were a reasonable approach. The covering of waste treatment facilities minimized nuisance problems in golf club (2341) and housing areas (172). Institutions such as hospitals have employed covered sprinkling filters (2619) to solve a nuisance and hygiene problem.

Covered sprinkling filters have been built during the period 1910 to 1920 to control nuisances (650, 1437, 1550, 5138). Again, in the late '30's (3397), industries such as those based on milk, found the use of covered trickling filters desirable. It was frequently published (1258, 2569, 3912) in the '50's that enclosed percolating filters were being used in Germany, France, and Austria. Quite often the population figure generating the sewage treated by the percolating filter plant was in the neighborhood of 6,000. This type of loading usually required two covered percolating filters, e.g., at Bad Vöslau (2569). In an effort to combat the nuisances of odor and insects, other processes have been tried, e.g., the anaerobic system described by Dewes (942). Equipment was also developed and patented such as that disclosed by Blunk (369).

Fly Control

Conflicting recommendations and operational experiences were published by Pönninger (3414) and Dahlem (853). Pönninger, with enclosed aerated trickling filters, found that within four to five weeks the filters were free from sludge and the upper layers had a large population of larvae and pupae of Psychoda. Dahlem stated that it was not necessary to enclose the filters completely to prevent odors, the troubles in cold weather, or the egress of flies in summer. The escape of flies can be prevented by enclosing the sides of the filter and by ensuring good distribution of liquid over the surface. Husmann (2145) agreed with Pönninger that the problem of the control of filter flies could be best solved by the complete enclosure of the filters. The flies can thus be confined within the filter without causing a nuisance. The larvae may be present in sufficient numbers to prevent accumulation of thick biofilm on the medium. Blunk (375) also supported the practice of enclosed filters to avoid trouble from flies. The flies which emerge from the top are trapped by the cover and destroyed by spiders. In the late 1950's, Kleeck (2506) discussed various methods of control of the filter flies. One of the most positive methods was to cover the percolating filter to prevent the laying of eggs.

Odor Control

Around the turn of the century, many communities, such as Mt. Vernon, New York; College Hill, Ohio; Chicago, Illinois; and many more, were aware of the problems of odor control (1721, 5130, 5308). The trickling filters were covered to prevent odors reaching nearby residences. Whether a filter was covered or not was often based on availability of funds and economics.

In 1935, Greeley (1557) described the progress of odor control by covered structures. In this country, as well as overseas, the control of odor by various means including enclosure was practiced. A limitation of enclosures was observed by Le Lan (2678). In his opinion, the media of all trickling filters should be renewed every five to six years, a difficult operation with enclosed filters. Several techniques of odor control were available, according to Blunk (373), but methods other than enclosure were expensive. Large metropolitan areas, such as Berlin (418), were concerned with methods of preventing odor and also the danger of corrosion caused by formation of sulfuric acid in covered plants already in use. Mount Vernon, New York, used covered bed and ventilation systems passing the foul odor through iron oxide for treatment (5130).

About 1940, Hurley (2115) reviewed the recommendations of the Royal Commission on sewage disposal (England), and considered the problems and methods of odor control, which included covering sedimentation tanks and using enclosed aerated filters. Husmann (2145) suggested that the cause of odor production in high rate filters was due to the septicity of the sewage being applied. By passing the air through the filter in the same direction as the sewage, the odor nuisance from decomposing organisms and sludge was prevented. Economics became even more important during the '50's, and low cost, geodesic shaped covers (1478, 5115) were used to trap the objectionable odors generated by waste treatment plants. A small single-stage enclosed trickling filter plant (4073) was built at a cost of $30.60 per capita compared to $25 per capita for open-type plants.

The tempo of odor control programs for waste treatment plants continued at a high rate during the '60's. Odor control units (3402) were installed in Port Washington, New York, an ozone generator in Coral Gables, Florida (4395), and digester gas was biologically treated by passing through the trickling filter (3405). Cheap enclosures such as fiberglas panels (5656) and reinforced concrete (4080) were shown to be quite effective.

Many industrial wastes have characteristic odors. Treatment plants handling canning wastes have been described by King (2492) to operate quite well using enclosed filters. Slop from the acid fermentation of molasses produces an odor nuisance and enclosed percolating filters have found some success, according to Krige (2571). Work on the treatment of phenolic effluent was done in England, and Hall (1651) stated that covered percolating filters in combination with activated sludge worked well. The successful operation of covered percolating filters for the sewage from a paraffin oxidation plant waste was reported by Christ (683) in 1958.

Several systems were developed and patents issued dealing with odor control. Yonner (4842) effectively applied forced aeration in covered filters. Odor control patents were issued to several people, e.g., Blunk (370), Reddie and Griffin (3523), Prüss and Blunk (3477), Gilde (1472), and Griffin (1597). These patents dealt with various means of enclosure, air recirculation, gas treating towers, and other process equipment.

Icing

Eddy and Vrooman (1088) in 1909 concluded that covered filters were required for complete success in winter operation. Ogden (3220) remarked that there was no advantage with porous walls (no side walls) and that the widely used revolving distributors were subjected to ice interference. Pritzkow (3465) stated that in an extremely large waste treatment plant icing was not a problem on the sprinkling filters even with temperatures as low as -16° in which the effluent temperature reaches

2°*. This statement was corroborated by Bantrell (167); he reported ice sometimes four feet thick on sewage filters at Rochester, New York. However, Walker (4579) observed in 1930 that enclosing the percolating filter gave slightly better oxidation, more efficient removal of bacteria, and less icing problems than open filters.

The advantages of enclosing the filters for winter operation were described by Cleland (711) in 1933. He stated that troubles caused by freezing of pipes and nozzles, especially during low night flow, could be eliminated by covering the trickling filters, resulting in a general increase in efficiency and less winter maintenance problems. Very poor results were obtained in winter operation at Cedar Rapids when ice reduced the ventilation of the filter beds (2918). The construction of elliptical concrete domes to cover the trickling filters, as reported by Molke (3056), protected them against the severe weather in Hibbing, Minnesota. During a comparison test of open versus enclosed filters in South Africa, Vosloo and O'Reilly (4560) observed that when the filters are overloaded, especially in cold weather, the open filters showed signs of ponding while the enclosed filters did not pond; however, the quality of the effluent deteriorated. Improved results found by other workers with enclosed aerated filters could be due to the greater depth of medium employed by them. Hurley (2125) in 1945 attributed the reason for the decrease in efficiency of percolating filters in cold weather compared to warm weather to the loss of scouring organisms for the surface layers. A paper was given by Taylor (4324) on the operation of percolating filters in Canada under severe weather conditions, with atmospheric temperatures 30° to 50°F below zero being recorded. He concluded that open percolating filters were unsuitable for districts where the winters were cold, but covered filters dosed either intermittently or continuously operated satisfactorily.

In locations where the average diurnal temperature is below freezing, the air in an enclosed percolating filter is maintained at 35°F (4509). Locations where the flow may be interrupted for periods of weeks or months, such as schools, have been operated quite successfully as closed filters (3591). Operation in Saskatchewan of open and closed percolating filters was described by Allen (52), who noted that it was almost impossible to operate the open filter in January and February. A concrete and fiberglas enclosure (2383) prevented icing of the filter even during periods of sub-zero temperature in Iowa.

Critique

Maintenance of biological trickling filter plants is required just as it would be on any mechanical or chemical process equipment. The literature reflects the awareness of workers in the field that maintenance is an important aspect. Further, it was observed that the usual techniques are not adequate for the development of new material and new operating procedures. Lack of awareness by taxpayers of the significance of maintenance of a waste treatment facility is apparent.

---

*This is a 1911 reference which does not specify whether the temperature is in degrees Centigrade or Fahrenheit. It appears likely that it is in degrees Centigrade.

The isolated one-unit waste treatment plant has been replaced by a multi-unit, large capital investment facility in which the taxpayers or the corporation have a prime interest. It is obvious, from this review of the literature, that operator training will increase to a higher level and that money will have to be made available for maintenance of these large capital investment facilities. Careful attention should be paid by the designing engineer to the new materials which have been developed and new processes which have been tried with the objective of a minimum maintenance system. However, the capital expenditure with the newer materials and processes should not exceed the present operating processes by any great extent, or make the new process uneconomical.

The nuisance control-aesthetic point of view has been a very strong consideration in covering waste treatment facilities, especially trickling filters. As the need for a more controlled environment increases with the demands of urban development, the time-tested approach will be used at a greater rate. The capital expenditure for the structure versus operational costs of other methods is very suitable for bond issue - tax-based applications. The little or no maintenance required by covers provides the treatment plant operator with additional time to concentrate on other solids-liquid treatment problems.

The filter fly, being a fragile organism, does not normally stray great distances from its breeding ground. However, concentrated swarms are produced which may be dispersed by wind currents. Enclosing the filter controls the dispersal of the filter fly. High organic wastes produce dense populations of flies and sludge growths. The beneficial effect of the fly larvae in loosening the sludge is maintained by using enclosures.

The use of covers to prevent icing has been shown to be of advantage. Plants may be operated under iced conditions with a great deal of effort and a loss of efficiency. The geographical location, i.e., temperature extremes, is a major factor in determining the necessity of covering the waste treatment system. Heating the ventilating air must be established for specific locations where low temperatures are common, but generally is not required.

The odor removal is partially solved by enclosure. Forced ventilation helps if it is in the direction of the liquid flow. Positive treatment techniques of sorption and/or oxidation of the odoriferous gas have been promising. The capital investment is higher for a covered system, but the net effect is a more complete waste treatment system. Removing the pollutant from the water and dispersing it into the air is only an intermediate solution and is not acceptable in the true environment management scheme of waste treatment.

SECTION XII

PERFORMANCE SUMMARY OF TRICKLING FILTERS

Performance of a sewage plant has been of major importance in the literature reviewed. For example, the British Royal Commission on Sewage Disposal, which was appointed in 1898, published conclusions and recommendations involving all phases of waste treatment (3983). The Commission reported in 1904 on the efficiency of the percolating filter relative to depth of bed and evaluated the performance of the filter versus a contact bed. Early efforts in this country (4326) and abroad (3360) were directed at evaluating the performance of various modified trickling filters and these efforts have been continued. Harris (1747), in 1925, compared treatment on percolating filters with that by activated sludge. During the construction of new plants, such as at Milwaukee (4440), alternative processes were pilot tested and the most reliable one chosen.

In the 1920's and 1930's, performance evaluations were directed towards the treatment of industrial waste effluent (665, 3466, 5231) and into some of the mechanics of biological purification (564, 3411). In an effort to evaluate the overall waste treatment picture, compilations were made listing the number of communities and the type of plants which were constructed or being planned (5104).

Throughout the 1940's many facets of industrial waste research, development, operation and management were studied (2704, 3344, 3764). Also, experimental plants (3689) were operated to evaluate the performance of new systems (3159) and the effect of process modifications (4645). Operators continued to have forums (5149) to discuss the evaluation of the performance of their plants.

In the 1950's work was being continued in evaluating the performance of trickling filters in handling industrial waste (3773, 4646). New developments in media for percolating filters were included (5568), along with evaluations of newly constructed waste treatment plants (1788, 4654). Process modifications, such as recirculation, were evaluated (267) and the literature was reviewed (363).

The 1960's were typified by further exploration of industrial waste treatment (318, 1102), process modification (1237, 1773), and additional descriptive information for a mathematical model of trickling filter theory (3917). More than 65 papers dealing with various aspects of mathematics applied to trickling filters appeared in the 1960's, 46 papers in the 1950's, 11 in the 1940's, 8 in the 1930's, 2 in the 1920's, 1 in the 1910's, and 4 in the 1900's.

MATHEMATICS USED FOR DESIGN AND PERFORMANCE EVALUATION

Design equations used to predict the performance of biological trickling filters began humbly with simple calculations, e.g., calculation of sprinkling distribution coefficients (1390, 2689, 3359, 4770) and calculation of mean contact time (4297). Mathematical deductions were made by Tatham (4296) in 1921 on the percentage purification obtained during a mean contact time which involved an additional variable called the "avidity constant." This constant, a numerical measure of the activity of the biological oxidation, was dependent on the type of waste being treated and the conditions for oxidation. A review of biological treatment dating back to 1671, which was written by Dibdin (946) in 1910, did not indicate any particular formalized mathematical expression for the prediction of percolating filter efficiencies. Investigators such as Imhoff (2184), Pönninger (3412), Escritt (1191), and Gaultier (1432) applied mathematical procedures for determining medium size, depth of bed, hydraulic load and cross-sectional area of filter beds, oxygen consumption values, concentration of sewage expressed by McGowan's formula, and air requirements. A booklet was prepared by Pöpel (2202) which outlined operations and calculations in connection with trickling filters.

Velz (4535) proposed that the performance of the percolating filter can be expressed by the equation: $\frac{L_D}{L} = 10^{-kD}$, where L represented the total removable fraction of BOD, D was depth, and L_D represented the quantity of removable BOD remaining at depth D. The velocity constant, k, was at temperature t°. Stack (4157) derived equations for the performance of percolating filters operated with and without recirculation. His equations were based on the assumption that a percolating filter was a self-regenerating absorption tower or that each unit depth of the filter will remove a constant fraction of the BOD applied to that unit depth. Howland (2063) proposed a modified equation, along these lines, which involved a temperature coefficient which was recommended to take into account the fundamental temperature effect on the biological process. Sorrels and Zeller (4111) found a hyperbolic relation between the applied BOD and that removed by primary filters in a two-stage operation.

Using the concept of the straight line formula ($y = mx + b$), Gerber (1456) interpreted y to equal the designed BOD divided by the applied BOD, m to be a coefficient equalling 0.0052, x to be the hydraulic dosing rate in feet per day divided by the product of the depth of the filter in feet and a reaction rate constant in units of reciprocal day. Using b to equal 0.07, Gerber stated that the curve was good up to a value of $x = 50$. Ingram (2222) suggested that a filter loading ratio (R_L), defined as the strength of sewage expressed in terms of depth of filter, area of filter, volume of sewage, and weight of BOD, provided a simple basis for calculating filter size. A similar concept was used by Gaillard (1391) who compared the performance of percolating filters in Johannesburg, South Africa, on the basis of a "load unit." The "load unit" was the product of the sewage strength (ppm oxygen absorbed from permanganate) and the rate of flow in gallons per cubic yard of medium per day.

Modified equations were proposed by Yakovlev and Galanin (4840), Meyer and Kirsten (2988), Bushee (552), and Tomlinson and Hall (44[illegible], which involved trickling filters operating with and without recirculation, the quantity of flow and concentration of the influent, deviations from nonstandard conditions, and two-stage monomolecular reactions. Schulze developed (3915, 3916, 3917) formulations to describe the filtration process which equated biological filtration to an adsorption process in which the hydraulic load determined the period of contact and, therefore, determined the efficiency of treatment. Zeller (4860) proposed a formula which included nitrogen loading. The BOD loading is a major factor in BOD removal by a trickling filter. The hydraulic rate is a minor factor and operates inversely as 0.5 power. McCabe (2895) proposed and defended a two-phase mathematical formulation which fits the laboratory and field data concerning the biooxidation of waste materials. The BOD removal is attributed to bioadsorption. The sludge growth during BOD removal is divided into the constant growth phase, the declining growth phase, and an auto-oxidation phase. The formula given for the relation between biooxidation and sludge growth rate is a two-phase discontinuous function. Hartmann (1770) proposed design equations to be used for evaluating the efficiency of the revived dipping contact filter concept. Melzer (2966) developed an equation which was compared with the law proposed by Velz and showed that data obtained agree more closely with the values calculated by the newly proposed formula than Velz's formula.

Recent foreign interest in performance evaluation has been expressed in the development of design and performance formulas by Kolobanov (2543), Tucek (4474), Kucharski (2583), and Ganczarczyk and Suschka (1404, 1405). These formulas involved variables similar to those used in this country, e.g., hydraulic load, height of tower biofilters or depth of bed, volume of air feed, temperature, biological activity, industrial waste fractions, aerating ability, and retention times.

Germain (1460) developed an equation for predicting performance of a trickling filter containing plastic media for domestic sewage containing a small amount of industrial waste. Mathematical models were reported by Swilley and Atkinson (4276) and Eckenfelder and Cardenas (1084) which used laboratory operation to develop necessary data. Further, Eckenfelder (1081) developed a relationship using average coefficients based on a statistical analysis of published data. This relationship was proposed to be used for the design of trickling filters treating domestic sewage and a hypothesis was proposed to explain the effects of oxygen transfer and temperature on the performance of the filters. Correlation between specific surface area, applied BOD concentration, and a removal rate coefficient was defined by Balakrishnan and coworkers (154). Roesler and Smith (3658) in 1969 proposed a mathematical model for trickling filters which involved capital cost, operation cost, and recirculation along with normal operating variables. Computer testing of field data agreed with the model.

Nomographs and Charts

Graphical expressions have been proposed in the form of charts and monographs for estimating the performance of standard percolating filters by Bernhart (283), and high-rate percolating filters by Newberry and coworkers (3174). Charts and graphs were used by Eliassen (1154), e.g., to determine optimum loading conditions and dimensions of filters by Sorreis and Zeller (4110), to determine the effect of recirculation by Eliassen (1150), to provide a rapid means of calculating filter capacity based on gallons of sewage per acre foot per day or on pounds of BOD applied per cubic yard per day, and to evaluate many combinations of hydraulic load, recycle, BOD loading and tower size by Mehta et al. (2955).

Walton (4596) prepared nomographs for determining the depth of filter required to produce an effluent which would impart a final river BOD of 40 mg/l under various conditions. Nomographs were used to quickly solve design equations, such as that of the Upper Mississippi Board of Public Health Engineers (2801) and the Trickling Filter Floor Institute (5574). A nomograph developed by Davis (885) shows the relation between BOD of settled filter effluent and that of crude settled sewage to BOD of filter effluent and the ratio of recirculated flow to flow of crude sewage. Rincke (3621) prepared a nomograph to be used for evaluating the performance of trickling filters which involved influent BOD, surface loading, depth of bed, load capacity, temperature, percent decomposition, and effluent BOD.

Statistics

Statistical considerations for performance evaluation of trickling filter are important throughout the literature; e.g., Childs and Schroepfer (670) reported statistics during analysis of data from trickling filter plants in 1931. Mohlman (3052) evaluated the data of the National Research Council gathered at military installations to determine the precision expected in the performance of trickling filters and other waste treatment plants. Statistical analysis and correlation of data obtained from 44 plants in the Upper Mississippi Valley States was undertaken by Fairall (1232, 1233) for the purpose of compiling general requirements for trickling filter design as reported in the Ten States Standards (5011). Pilot plant data were analyzed statistically (352, 1400) to determine the performance of single- and two-stage operations, the effect of BOD loading, temperature and recirculation. The deviation in measured parameters between several replicate pilot filters was, for example, the mean standard deviations of BOD = 6.7 ± 1.6; permanganate value = 11.5 ±1.2, ammonia nitrogen = 5.9 ± 2.8; oxidized nitrogen = 32.6 ± 2.5, as reported by Gameson et al. (1400). Statistical measurements were used by Oldaker (3227) to evaluate chemical and biological studies on flax waste stabilization, temperature effects on trickling filters by Schroepfer et al. (3903), detention times using radioisotope techniques by Eden and Briggs (1107), comparison of double filtration and alternating double filtration while treating industrial waste by Hawkes and Jenkins (1827), and proof of the advantages of plastic biological filtering media in handling specific industrial wastes by Chipperfield (678).

Formula Evaluations

The papers which referred to the evaluation of proposed formulations, such as noted by Rankin et al. (3501), contributed materially to the discussion of the performance mathematics of biological trickling filters. Hardenbergh and Rodie (1731) used the design equations developed by the Subcommittee on Military Sewage of the National Research Council (5590) to evaluate the performance of single-stage and two-stage filters under varying load and recirculating conditions. The National Research Council formula (5590) for efficiency was proposed to involve the weight of BOD in raw settled sewage (w) applied to a filter volume (V) for the number of passes (F) as follows:

$$\%\ \text{Efficiency} = \frac{100}{1 + 0.0085\sqrt{\frac{W}{VF}}}$$

The recirculation factor (F) was defined as:

$$F = \frac{1 + R/I}{(1 + 0.1\ R/I)^2}$$

where R/I was the recirculation ratio.

In 1952, Walton (4595) applied the National Research Council formula to predict the performance of new treatment plants in Texas. Wishart (4793) commented on the importance of collaboration of investigators to supply data gathered on full-scale, pilot plant, and laboratory work to produce generally applicable formulas, e.g., the National Research Council's formula.

Homack (3502) criticized the conclusion given by Rankin (3502) on the use of three methods of evaluation of the Biofiltration process where the Velz formula checked most accurately with actual data. Homack questioned if the dominant factor in the performance of a trickling plant is the ratio of circulation. However, Nelson and Lanouette (3161) successfully applied the National Research Council formulas to high-rate biological filters. Climatic factors were also evaluated by Benzie and coworkers (273) based on the performance relationships of the National Research Council and Great Lakes-Upper Mississippi River Board. It was found that there was a significant difference in filter efficiencies between summer and winter.

Behn (246) discussed mathematical formulations on the process with and without recirculation as proposed by Phelps, Velz, Schulze, Howland, and Stack. Special emphasis was placed upon reaction kinetics and the role of recirculation. Further work was suggested to determine the validity of first order relationships, the time versus depth as a basis for BOD extraction, the concept of filter saturation, and the role of filter medium in filter saturation and time of contact. A formula was proposed by Sima (4031) and compared with the formulas of the National Research Council, from which it was concluded that the Council's formulas gave the best results, but involved much more work than the one proposed.

Galler and Gotaas (1395, 1396, 1397) presented an analysis of biological filter variables which eventually led to the optimization of these factors to be used in design formulations. Archer and Robinson (85) investigated single- and two-stage biological filtration along with medium volume and recirculation ratio and found that predictions of efficiencies could be adequately expressed by the National Research Council performance formulas. Baker and Graves (150) compared the trickling filter efficiency formulas proposed by the National Research Council, Eckenfelder, and Galler and Gotaas. Based upon a computer optimizing program, they determined that minimum volumes of media would occur when the volumes in each stage of a two-stage process were equal when the NRC formula and a modified Eckenfelder formula were used. A ratio volume of the first to the second stage of 1:2 occurred if the Galler-Gotaas formula was used. A statistical analysis of trickling filter performance formulas was reported by Robertson et al. (3647) to determine, among other things, the accuracy of the existing design equations in predicting the performance of the filters and the possibility of improving predictions by the adjustment of certain parameters using regression analysis. Based on about 4,000 single observation datum points, the formulas of Velz, Schulze, Stack, Rankin, National Research Council, Farrell, Germain, and Galler and Gotaas (all put in common nomenclature) were subjected to rigorous analysis (3647). An over-simplification of the conclusions reached was that the Galler and Gotaas equation for domestic waste water could be used to fit the predictions of trickling filter treatment of paper mill waste better than the others considered.

Defined Functional Relationships

Many additional mathematical studies were published which dealt with determining the mean residence time in a trickling filter (99, 364, 1449, 2064, 2065, 2904, 2964, 4042, 4207). An in-depth review of these investigations was presented by Sheikh (3981), who found that the mean retention period used by many workers was inadequate to define the retention characteristics of a filter. Sheikh used the modal time and the standard deviation of the log-normal distribution to derive and compare expressions for filter performance. Additional mathematical evaluations have been reported by Ames, Behn and Collings (68) involving the transient operation of trickling filters, investigations of turbulent flow on vertical walls by Belkin et al. (250), and the effect of particle shape on porosity and surface area of media by Schroepfer (3902), and Ganga (2377) on the performance of the filters. Mathematics involving growth kinetics of the biological film (3824), the role of diffusion in the rate of biological uptake of organics (1621), oxygen demand of microorganisms (3428), and mass transfer of nutrients (2838) are typical of the large number of mathematically oriented papers which have been published in the last decade and a half. Mathematical models have also been proposed for laboratory conditions (548), as well as on the basis of published literature for the biological oxidation of industrial wastes (1077) to provide new tools (1085) for performance evaluation by designing engineers.

Critique

Sufficient efforts have been reported to define the primary variables and identify functional models which may be used for design and description of filter performance. Solutions to previous questions, such as the order of mathematical relationships, the effect of recirculation on efficiency, and the relation of contact time or medium depth to performance, have been investigated. Unfortunately, the answers have not been reported in as straightforward a manner as those of the National Research Council. It appears that the advent of the computer has brought into the field investigators who may be more interested in the functions of the mathematics than in applying the mathematical functions to practical performance evaluation and prediction. It would be highly desirable to extend the work of Robertson et al. (3647) to other data and report the results in a usable manner. It is agreed and understood that the functions of the filter are complex, but approximations can be made and a rationale developed. This rationale must satisfy theory, but be applicable to real problems based upon measurable parameters.

TREATMENT EFFICIENCY

The importance of determining the efficiency of treatment plants has been reported by Chase (658) from the standpoint of design and operation. Studies were made by Knechtges (2516) and Fairall (1233) on the hydraulic and organic loadings and of biological trickling filters and their modifications. Childs and Schroepfer (670) studied the effectiveness of the usual parameters, e.g., five-day biochemical oxygen demand, and suspended solids removal taken on 24-hour composite samples, for determining treatment plant efficiencies. The large quantity of information developed on the nitrogen balance in sewage during biological filtration made it possible to develop a performance formula which included the nitrogen loading (4860).

Hydraulic and Organic Loading

The literature has a large number of reports dealing with hydraulic and organic loading of the standard rate of low rate single-stage biological trickling filter, such as those by Schulze (3916), Grantham (1542), and Beatty (232). Efficiency is affected by organic and hydraulic load with recirculation in two primary ways: an increase in the organic load affects the effluent quality more than an increase in the hydraulic load, and,as either load is increased, the total amount of BOD removed increases, but the percentage removal decreases, giving an effluent of lower quality.

Overall reductions in suspended solids (94%) and BOD_5 (93%) were reported by Lose (2762) on the 110-foot diameter trickling filters of Chatham, New York, which were designed to treat a maximum daily flow of 500,000 gal. A waste treatment plant at Albemarle, North Carolina, designed to treat 1.75 mgd (3081) performed similarly,with the average removal being 90% for suspended solids and 80 to 95% for BOD_5 (with post-treatment). Performance of the Princeton, New Jersey, waste treatment plant was affected by flooding the filter, which then discharged an effluent which was four times the normal 15 to 20 mg/l BOD_5. Even though slightly overloaded, Hasfurther (1788) reported that the new biological filter at Fairfield, Illinois, reduced the BOD by 92.5% and the final effluent contained 8 to 18 mg/l nitrates. Digester supernatant liquor (3767) at loadings up to 400 mg/l BOD was effectively reduced by 80 to 87% by a trickling filter loaded at the rate of 1 mgad (23 gal./ft^2/day).

Some of the industrial wastes which have been treated by biological trickling filters are as follows:

1. Gas Liquors - loaded at 70 gal./yd^3/day (about 250 lb of BOD/1,000 cu ft/day) produced 60 to 70% phenol content reduction when the gas liquor was kept between 0.5 and 1% of the influent (1413).

2. Refinery Wastes - loaded at 9 to 29 mgad (207 to 667 gal./ft^2/day) with recirculations of 1.5 up to 5 and BOD$_5$ loadings of 400 lb/ac-f/day (92 lb of BOD/1,000 ft^3/day) produced satisfactory effluents (2891).

3. Flax Wastes - 1% concentrations were treated at a BOD$_5$ loading of 500 lb/ac-f/day (11.5 lb of BOD/1,000 ft^3/day) and produced 57 to 72% removal (3226).

4. Canning Wastes - were treated, after screening, to 80% - 95% BOD$_5$ removal at loadings of 1/2 mgad (11.5 gal./ft^3/day) and loadings of 2 mgad (46 gal./ft^2/day) dropped the efficiency to 50% - 70% (2486).

5. Tomato Canning Wastes - with BOD of 548 mg/l and 275 mg/l suspended solids were loaded at a rate of 0.724 lb BOD$_5$/yd^3/day (26.8 lb BOD$_5$/1,000 ft^3/day) and resulted in 70% BOD$_5$ removal, producing an effluent with a BOD of 161 mg/l (1900).

6. Packing House Wastes - of 1,000 to 2,000 mg/l BOD$_5$ and 200 to 2,000 mg/l suspended solids were treated to 70% BOD removal with a recirculation of 3:1 on a 4 mgad (92 gal./ft^2/day) treatment plant (1716).

7. Laundry Wastes - were treated at 0.5 mgad (11.5 gal./ft^2/day) to give 85% BOD$_5$ reduction, 1 mgad (23 gal./ft^2/day) to give 76% reduction, and 2 mgad (46 gal./ft^2/day) to give 62% reduction on a waste stream which had been subjected to chemical pretreatment (433).

8. Kraft Pulp Mill Wastes - were treated at a BOD$_5$ loading of 1,420 g/m^3/day (87 lb of BOD/1,000 ft^3/day) and a hydraulic loading of 1.53 m^3/m^2/day (37.5 gal./ft^2/day) to produce BOD$_5$ reductions of 80% (3207).

9. Chipboard Wastes - were treated to 85% BOD$_5$ removal with organic loadings of 15 lb of BOD/1,000 ft^3/day and hydraulic load less than 1 mgad (23 gal./ft^2/day), but with a recirculation ratio of 1:1 BOD$_5$ removals were 93% at the same organic loading and a total hydraulic loading less than 2 mgad (46 gal./ft^2/day) (3593).

A two-stage biological trickling filter was studied by Sorrels and Zeller at loadings from 32 to 69 lb BOD$_5$/1,000 ft^3/day.

An increase in BOD$_5$ and suspended solids removal in both the primary and secondary filters was observed with increased load. Ammonia nitrogen oxidation was also reduced, which suggested that for an equal volume of sewage series filtration was better for treatment than parallel filtration. Two-stage filter operations loaded organically at 1,000, 2,000, 3,000, and 4,000 lb BOD/ac-f/day (23, 46, 69 and 92 lb BOD/1,000 ft^3/day) and hydraulically at 4.46, 8.92, 13.38 and 17.83 mgad (102, 205, 307 and 410 gal./ft^2/day) indicated that the total reduction in BOD in the primary filters increased with increased loading up to 3,000 lb/ac-f/day, (69 lb BOD/1,000 ft^3/day), but fell at the loading of 4,000 lb (92 lb of BOD/1,000 ft^3/day). Effluent BOD of 3,690 mg/l from the Porteous process (a heat sludge-conditioning process) was loaded at 50 gal./yd^3/day on a two-stage filter and produced effluent BOD's of 500 and 86.7 mg/l, and the settled effluent was 38.3 mg/l (2783). After further investigation (2783), it was determined that the primary filter could be loaded at rates of 156 gal./yd^3/day and the settled effluent could be applied at 72 gal./yd^3/day to the secondary filter to yield substantial BOD removal.

Industrial wastes such as that of compressed yeast manufacture were treated on two-stage operations with no recirculation at loadings of 300 to 2,800 lb BOD/ac-f/day (6.9 to 64 lb BOD/1,000 ft^3/day) and produced reductions of 50% BOD (3769). A marked decrease in efficiency was observed (3769) at loadings in excess of 1,200 lb BOD/ac-f/day, (27.6 lb BOD/1,000 ft^3/day), but performance was not significantly affected by flow rates between 0.19 and 1.73 mgad (4.4 and 40 gal./ft^2/day). Pharmaceutical wastes were treated (1941) by two-stage trickling filters loaded at 2.43 mgad (55.5 gal./ft^2/day) and an average BOD of 13,000 mg/l which produced 96% removal. Milk wastes were treated by two-stage filtration (4802), in which the first-stage filter removed an average of 1,350 lb BOD/ac-f/day (31 lb BOD/1,000 ft^3/day). The second-stage filtration increased the total reduction to 90.4% BOD$_5$ removal,with effluent having the desirable properties of dissolved oxygen, nitrates and alkalinity.

Converted high-rate trickling filters in Baltimore, Maryland, were operated from 6.5 to 26 mgad (150 to 600 gal./ft^2/day) during which the highest loading rate still produced 50% BOD removal. It was noted by Keefer and Meisel (2404) and Keefer and Kratz (2396) that by loading between 2.68 and 16.39 mgad (62 to 377 gal./ft^2/day) 77.3 to 91% removal was achieved, while with loadings of 2.68 to 13.53 mgad (62 to 311 gal./ft^2/day) 80% BOD removal was experienced. Experiments in Chicago (3045) were conducted with a hydraulic loading of 20.2 to 26.6 mgad (465 to 612 gal./ft^2/day) in which the raw sewage containing 97 mg/l BOD and 122 mg/l suspended solids was reduced to 12.3 and 44 mg/l BOD, depending on the season. The Upper Mississippi River Basin Sanitation personnel (4759) investigated high rate percolating filters treating domestic sewage in conjunction with trade wastes. Plants using two-stage high rate treatment had overall efficiencies of 83.6 to 95.1% BOD removal, but single-stage treatment resulted in 57.5 to 91.4% removal. Suspended solids removal in the two-stage operation was 88.6 to 94.3% with organic nitrogen being removed in the two-stage process by 28 to 64%. Provided the organic load was less than 1,000 lb of BOD/1,000 ft^3/day, when the hydraulic load of the filters was between 7 and 30 mgad (26 to 690 gal./ft^2/day), the reduction in BOD was proportional to the load (4759).

Roughing filter applications with 13 to 15 meter (43 to 49 ft) deep beds (2988) handled phenolic and fatty acid wastes at organic loads of 1,000 mg/l of BOD which reduced the phenol concentrations of 500 to 950 mg/l down to 1 mg/l. Plastic media were used (513) to treat phenol waste to 82% removal at hydraulic loadings of 11 mgad (253 gal./ft^2/day) and 85 lb BOD/1,000 ft^3/day.

Food processing and milk waste waters (1157, 5325) were treated effectively on roughing filters. Seventy-five percent reduction in chemical oxygen demand was experienced for the milk waste (1157) that was loaded at approximately 71 mgad (1,633 gal./ft^2/day) and 8.8 lb of COD/1,000 ft^3/day.

Trickling filter towers loaded at 3,100 to 3,900 grams of BOD per cubic meter per day (0.23 to 0.30 lb BOD/1,000 ft^3/day) produced a reduction of 71% in BOD. The two-stage operation handled a load of 3,000 to 3,500 grams of BOD per cubic meter of medium (0.23 to 0.27 lb of BOD/1,000 ft^3/day) and produced 91% reduction in BOD with 83% of the organic nitrogen being removed in the last stage (3910). Optimal surface loading of high rate filters was found to be 0.8 to 1.0 m^3/m^2/hr (475 to 590 gal./ft^2/day) and the optimal organic loading was 0.8 to 1.1 kg BOD/m^3/day (50 to 69 lb of BOD/1,000 ft^3/day) (4030).

Greater efficiency was experienced in BOD reduction when operating at the rate of 10 mgad (230 gal./ft^2/day) than at an average rate of 1.1 mgad (25 gal./ft^2/day) (383), when treating industrial wastes from cotton finishing. A cotton mill waste (350 to 600 mg/l BOD) was treated adequately on a high-rate biological filter (2688) at 28 mgad (645 gal./ft^2/day). Milk and packing house wastes were treated on high-rate filters of various media (2701) to 15, 43.4, 48.8, and 49.4% BOD reduction and were loaded at 16 mgad (368 gal./ft^2/day). After sedimentation, BOD reductions were 80 to 90% with significant increase in nitrification (2701). The BOD removals per acre foot of filter were 350 to 410 pounds (8 to 9.4 lb BOD/1,000 ft^3/day) at 2 mgad (46 gal./ft^2/day) and 2,200 to 2,600 pounds at 16 mgad (50 to 60 lb of BOD/1,000 ft^3/day at 368 gal./ft^2/day).

Gas plant, milk, sugar refinery, and tannery wastes were treated by biological filtration (1138). Phenolic wastes were loaded at 1 mgad (23 gal./ft^2/day) and the greatest removals attained were 4.72 lb of BOD/1,000 ft^3/day of medium with concentrations of 100 to 115 mg/l phenol. When loaded at 16 mgad (368 gal./ft^2/day) with the milk processing waste the BOD was reduced 90.6%, with the influent BOD of 537 mg/l and the effluent BOD of 46 mg/l.

High-rate trickling filters have treated chemical wastes containing organic oils and acids and up to 5,000 mg/l of formaldehyde (300 to 10,000 mg/l BOD$_5$) that were diluted and applied at 50 mgad (1,150 gal./ft^2/day). The formaldehyde content was reduced to 46 mg/l with an 82% BOD reduction. By treating the composite waste waters of the chemical plant (948), 94.5% of the formaldehyde was removed. High-rate or tower percolating filters provided adequate treatment loaded at 24 m^3/m^2/day (590 gal./ft^2/day) for a waste (100 mg/l of BOD) which was subjected to an oxygen capacity of 750 g/m^3/day (46.8 lb/1,000 ft^3/day) (3125).

A modification of the trickling filter, the Prüss enclosed filter (1691), treated 3.5 to 24.2 gal./yd^3 of media per day (130 to 892 gal./1,000 ft^3/day) of domestic sewage and produced an effluent with a BOD of 16 to 80 mg/l. The Aero-filter was loaded (1667) with a waste (4,000 to 8,000 mg/l BOD) at 25 mgad (575 gal./ft^2/day) and produced a 95 to 97% BOD reduction on a diluted influent. BOD loadings of 18 to 20 lb/yd^3/day (666 to 742 lb BOD/1,000 ft^3/day) were applied to a Biofilter to produce 90% BOD reduction of a distillery waste (20,000 mg/l BOD). It was further noted (1284) that the hydraulic loading should not be less than 48 mgad (1,104 gal./ft^2/day) or greater than 100 to 125 mgad (2,300 to 2,875 gal./ft^2/day). The Accelo-Filter was reported by Gillard (1475) to treat normal domestic sewage with 100 to 200% of the average flow recirculated, and generally it was expected that a BOD reduction of 80 to 95% was achieved.

Use of trickling filters and activated sludge was described by Oldaker (3227) for the treatment of flax waste. The activated sludge reduced the flax waste BOD by 15 to 18% after 24 hours and by 53 to 59% after 54 hours. The percolating filters took a recirculation ratio of 3:1 with a hydraulic loading of 3.5 mgad (80.6 gal./ft^2/day) and 649 pounds BOD/ac-f/day (14.7 lb of BOD/1,000 ft^3/day) to produce 88% removal or 1,432 pounds BOD/ac-f/day (33 lb of BOD/1,000 ft^3/day) to produce 71% removal. Treatment at Greenville, South Carolina, on combined textile finishing waste indicated that to produce a BOD reduction of 70 to 80% a hydraulic loading of 4 mgad (92 gal./ft^2/day) was used, but the BOD loading must be less than 3,000 pounds/ac-f/day (69 lb of BOD/1,000 ft^3/day).

This treatment was followed by an activated-sludge process which would produce a final effluent of less than 30 mg/l BOD (1464). A septic tank followed by a contact bed treatment plant was replaced (1952) by settling tanks and trickling filters to handle food processing waste (influent BOD 220 to 1,230 mg/l) and were loaded at 1.5 mgad (34.5 gal./ft^2/day) to produce 95% BOD removal.

Imhoff tank-trickling filter plants were reported by Drury (1037) to be aided by 15 to 30 minutes' aeration which reduced the BOD by 20% and allowed increased trickling filter loadings of 400 to 500 pounds BOD/ac-f/day (9.2 to 11.5 lb of BOD/1,000 ft^3/day) for dosing of 16 mgad (368 gal./ft^2/day). Wastes from rayon manufacturing were reported by Roetman (3659) to be treated on percolating filters at the rate of 1 mgad (23 gal./ft^2/day) and 300 pounds BOD/ac-f/day (6.9 lb of BOD/1,000 ft^3/day) to 90% removal, and by using the effluent from Imhoff tank at a rate of 1,050 pounds BOD/ac-f/day (24.1 lb of BOD/1,000 ft^3/day) to complete removal, as measured by the BOD test. Microstrainers and sand filters were used (3187, 5184) as treatment after the filters and decreased the suspended solids in the effluent from 30 to 110 mg/l to less than 20 mg/l, with 75% as an average reduction.

Critique

The efficiency of trickling filters has been reported in numerous domestic and industrial applications. However, the usual percent removal and the occasional hydraulic and organic loading information may not be adequate criteria to determine performance. Specific data dealing with enzymatic rates of biological activity and general information on nuisances and operational problems have been published in an effort to supplement the usual performance efficiency. It is apparent from the reviewed literature that the performances of biological trickling filters were variable from the standpoint of background, design, construction, operation, and maintenance.

Both hydraulic and organic loadings of the filter have been described as being the dominant factor in treatment performance. To summarize expected performance of biological filtration is extremely difficult and, perhaps, misleading. However, some performance information should be provided in every paper for comparative purposes. The following comments in Table 5 are submitted for the novice, not the expert or practitioner, and it should be fully understood that exceptions may be raised with valid reason.

It is to be carefully noted that the information in Table 5 may change if the waste water fluctuates in strength and flow, toxic elements are available, and limitations are imposed upon the physical plant. The value of observing these data is that these figures have been reported on a variety of waste water and conditions of treatment. One may view this information in light of its source, i.e., the performances of operating plants have been described and it should not be difficult to design other plants to duplicate the performance of the trickling filters.

Table 5

Summary of Filter Criteria

Filtration Rate	Filter Stage	Usual Equipment Modification	Expected Efficiency, %	Possible Improvements
Low	Single	Clarifier	60-70	Recirculation Additional stage
Low	Two	Clarifier Recirculation	90+	Nutrient removal Alternate system
High	Single	Clarifier	40-50	Additional stage Recirculation
High	Two	Clarifier Recirculation	85	Alternate system Nutrient removal
Super	Single	Deep bed	50	Clarifier Recirculation
Super or High	Single	Followed by activated sludge	95+	Sludge handling Recirculation Alternate system

Bacterial and Viral Removal

The performance of biological filters in reducing the bacteria and virus particles has been the subject of numerous papers. General bacteriological studies by Malguth (2849) indicated that there was a continual decrease in the number of bacteria in each unit of the waste treatment plant and the average final percentage reduction was 95% at 37.5°C (99.5°F) and 94.3% at 20°C (68°F). Coffin and Hale (731) discussed in 1916 the effects of treatment units on bacteria reduction. The septic tank reduced the total number of bacteria by 72% and *Bacterium coli* by 40%. Primary contact beds reduced the total number of bacteria by 16% and *B. coli* by 15%. Settling basins removed an additional increment (731), e.g., total number of bacteria by 2% and *B. coli* by 13%, and sand filtration removed 91% of *B. coli*. Effluent chlorination destroyed a 99.9% of total bacteria and 99.997% of *B. coli*. Similar data were published by Allen and Smith (48), in which they showed that percolating filters and humus tanks removed 97.2% of *B. coli* and 98.3% of *Streptococcus faecalis* from settled sewage, which gave a total treatment plant reduction in these bacteria of 98.68% and 99.40%, respectively. Septic tanks followed by trickling filters removed B. coli by 89 to 97%.

Endamoeba histolytica cysts were reduced by 50% in primary sedimentation and 90% due to trickling filter with secondary clarification, according to Kott and Kott (2553). However, cysts of Endamoeba histolytica were reported in sewage influent in Israel (2552), but after biological filtration cyst counts were very low or no cysts were found. Average bacterial reductions reported of ten waste treatment plants (4245) indicated that total bacteria count was reduced 95.9% without chlorination and 99.8% with chlorination, while the B. coli were reduced 99.6% without chlorination and 99.98% with chlorination.

The relationship between the efficiency of the filter operation and the number or organisms present was discussed by Nakajima (3144) and it was recommended that the optimum BOD loading was 900 ± 100 g/m^3/day (56.1 ± 6.2 lb BOD/1,000 ft^3/day). While checking for tubercle bacilli, Müller (3115) found that in the sludge from lightly loaded percolating filters there was a positive indication in 90% of the samples, while 29% to 50% of the samples of sludge from high-rate filters and activated sludge were positive. The bacterial activity of the biofilm was reported by Pöhl (3401) to be so great that a depth of one-half meter (19 inches) was sufficient for purification if the waste was applied intermittently and frequently in small amounts well distributed over the whole surface. Rudolfs et al. (3739) also reported that B. coli reduction was the greatest in the upper half of the filtering bed (2 feet) where the protozoa were the most numerous. Research by Knop and Husmann (2524) has shown that two-stage trickling filter operations produced a better removal of Bacterium coli than single-stage, but the advantages did not offset the installation or operational cost. Allen et al. (40) supported the conclusion reached by Knop and Husmann that two-stage filters provided better bacterial removal.

Investigations showed that sewage in the Birmingham Tame district (4933) with a high percentage of trade wastes contained less bacteria than a weak domestic sewage. Studies at Pennsylvania State College (3248, 4579) indicated that closed percolating filters gave slightly better removal of bacteria than open trickling filters. Effluent examinations by Brauss (448) revealed that irrigation fields removed more total bacteria and B. coli than percolating filters. Low-rate percolating filters were preferred, however, by Neumeyer (3172) to that of high-rate filters because of the better bacterial count reduction. While comparing various units of an Imhoff-trickling filter plant, Hotchkiss (2044) noted that the effluent from the sprinkling filter contained the fewest bacteria compared to other systems studied. Biofilter operations in New Zealand were reported by Rowntree (3707) to provide a high degree of treatment in which B. coli was absent from the final effluent.

In an attempt to aid bacterial removal, aeration was proposed as an auxiliary to trickling filter treatment (3605). It was found that the value of the aerator was mainly in the reduction of biochemical oxygen demand and in flocculation of part of the colloidal matter, but that there was no reduction in B. coli. During a discussion of bacteria and effluent quality of percolating filters, iron bacteria and sulphur bacteria were reported (2252) to be found in the effluent from series operated percolating filters, but not in the effluent from single filters. Interest was expressed by Hurley (2120) and Grigorieva (1603) on the effect of biological trickling filtration on viruses and various other forms of microorganisms.

Kabler (2364) reviewed work on the effect of biological filtration on pathogenic bacteria, fungi and viruses and indicated that more efficient methods were needed for enumerating these life forms in sewage. Aerobic and anaerobic treatment were investigated on bacteriophages (985) and indicated the resistance of this life form to normal biological treatment. Human enteric viruses in sewage were studied by Clarke and Kabler (702) and they concluded that primary treatment has little or no effect on the virus; however, biological filtration reduces viral numbers by about 40%, while activated sludge reduces them by 90 to 98%. Similar work reported by Shuval et al. (4011) indicated that only about one-third of the phages present were removed during treatment which indicated that biological filtration plants are ineffective in removing viruses.

Coxsackie A-13 virus was observed (2243) to pass through both activated sludge and trickling filters and, was controlled only by chlorine dosage of 0.5 ppm with 8 hours' contact. In continuing studies on the efficiencies of mechanical-biological treatment of sewage, Schutt (3920) added known numbers of Staphylococcus phage 3C, with radioactive sodium used as a tracer. He concluded that there was similarity in the removal of radioactivity and the inoculated phage, and that inadequate purification efficiency of percolating filters was demonstrated. Mundel et al. (3122) expressed concern on the viral carry-over from humus tanks following trickling filters and concluded that vegetables grown on land irrigated by this liquid should be cooked before consumption by human beings.

Bacterial removal efficiencies reported by Rudolfs et al. (3731) indicated that up to 90% of B. coli was removed in the upper 2.5 feet, where most of the bacteria-feeding protozoa were to be found on the trickling filter.

Helminthic ova were reduced by 18-26% by biological filters, whereas Imhoff tanks removed 97% and, when followed by secondary sedimentation tanks, removed 87% of that remaining (4125). Helminthic ova were in the crude sewage (316) in India, and after two-hour sedimentation 50 to 70% was removed, whereas treatment with percolating filters or activated sludge reduced them by 90 to 100%.

Allen et al. (46) concluded that percolating filters removed 80 to 90% of the bacteria and that further treatment on sand filters would improve the bacterial effluent quality but could not be relied upon. A high-rate biological filter was reported by Rabinowitz (3496) to reduce the coliform count of 16 x 10^7 organisms per milliliter in crude sewage by 70 to 90%. Using a membrane filter method of testing the efficiency of biological sewage treatment plants, Beling et al. (249) showed that the percolating filter is important in the removal of intestinal bacteria. The complete sewage treatment resulted in an average reduction of 94.5% in total bacteria and 93.7% in *B. coli*. High-rate filters were reported (5181) to remove 75% of the bacteria from a spent coke oven liquor and produced an effluent of acceptable quality.

Effect of medium and seasonal changes was noted by Tomlinson et al. (4428); e.g., the number of coliform bacteria in the settled sewage were higher during the warmer months, but the total bacteria count showed no regular seasonal variation. Filters containing four different kinds of media produced a 95% reduction regardless of the medium. Typical of industrial waste investigations was that reported by Dickinson (960) who observed that the bacterial reduction during treatment of a cannery waste on a percolating filter was 37 to 99% at 37°C (97°F). Heukelekian (1917) reported that the coliform bacteria were reduced to a greater percentage during the summer than in the winter on the Biofilter investigated, with the sedimentation tank considered as part of the unit. The percentage reduction of the total bacteria bore no relation to the percentage reduction of the coliform, but generally 90% reduction was achieved.

Chlorination, of course, has been the workhouse for disinfection and bacteria kill for many years. Mebus (2947) stated in the 1920's that the *B. coli* were reduced 99.992% during sewage operations, which included chlorination. Chlorine was used by Shuval et al. (4012) effectively for virus control and they obtained 99.9% reduction in virus concentrations and coliform counts with MPN (most probable number) less than 100 per 100 ml. Reference to the effect of chlorination on *Coxsackie virus A-13* has already been made. Chlorination following percolating filter treatment was reported by Goodwin (1518) to reduce the bacteria content by more than 99%. After chlorination of trickling filter effluent, bacterial contents were 144/cc at 37° (2574) and 3 to 38/cc (4212), with *B. coli* reductions down to 4.2/cc (2574), and no counts/cc (2852, 4212). In 1928, a waste treatment facility at a recreational area, consisting of a septic tank and trickling filters with post-chlorination, was able to remove 99.99% of *B. coli* (5088).

Critique

Biological trickling filters have demonstrated effective and economical removal of bacteria during the treatment of sewage. An awareness of the importance of bacterial removal was basic in the literature. Some divergent opinions expressed over a period of several years probably indicate the changes in the identification and isolation techniques more than changes in treatment plant efficiences. Soluble organic removal and bacterial removal may be generally considered as responding similarly in a treatment system; e.g., a system reducing 90% of the BOD will provide high bacterial removal, but a low BOD will indicate low bacterial removal. There are conditions, such as roughing filters, where a sizable BOD removal may be achieved, but without proper post-treatment, the bacterial removal may be low. There is considerable evidence that trickling filters do not provide adequate treatment for virus removal. However, the testing procedure for enumerating viruses leaves much to be desired and additional work is underway to improve this situation.

Disease Prevention

Disease transfer was recognized as the major problem to be faced in waste treatment. Diseases transmitted by sewage were reported by Wilson (4753), e.g., cholera, typhoid, paratyphoid, dysentery, Malta fever, Weil's disease, tuberculosis, anthrax, and poliomyelitis. Requirement standards have been established since 1910 (3261) that the effluent from a facility must be unobjectionable and practically free from typhoid and other pathogenic germs. Under normal conditions, the objective of the sewage works treatment was to eliminate the risk from infection from the effluent (4753); however, the effluent should not be used for irrigating crops which are eaten raw, and during epidemics the effluent should be disinfected. Hardy (1735) considered that the risk of infection transported by birds and insects to reservoirs or water supplies had been over-emphasized.

Work dealing with the control of disease transfer was reported in California (4960), where a three-year survey of direct utilization of waste waters was successfully conducted. Ingram (2220) compiled a selected bibliography dealing with organisms associated with processes of sewage treatment, including *Sphaerotilus*, zoogloeal bacteria and parasitic organisms causing disease.

Waste waters from a tuberculosis sanitarium, reported by Rutz and Weigmann (3794), were treated by biological filtration with chlorine post-treatment. Kabler's (2363) review of several investigators' work on pathogenic organisms indicated that enteric bacteria, viruses and tubercle bacteria were reduced considerably by biological filtration and other aerobic processes. However, Heukelekian and Albanese (1925) investigated sedimentation, septic tanks, biological filtration, and activated sludge, and indicated that all were ineffective in removing *Mycobacterium tuberculosis* from sewage. This work supported the earlier work by Jensen (2317), who showed that sedimentation tanks, Imhoff tanks, or percolating filters handling waste from tuberculosis sanitaria or slaughter houses in which tubercular animals were killed all had *T. bacilli* in the effluent (control was effected only by chlorination). It was demonstrated by Jusatz (2358) prior to the above two papers that treatment of sewage on a trickling filter does not prevent the appearance of *Myco. tuberculosis* and that they may be killed by adding sufficient chlorine to kill *B. coli* and reduce the bacterial count by 99 per cent. Studies carried out by Bhaskaran et al. (317) in Calcutta on waste waters from sanitarium and slaughter houses indicated that viable *Myco. tuberculosis* found in 95% of the sanitarium sewage samples and that biological filtration was not very effective in removing these organisms. No tubercle bacteria were found in the 33 samples of slaughter house waste waters which were taken at different times. A special plant designed for the waste waters from Gauting Sanitarium (near Munich) (4471) handled the waste of a thousand patients and a staff of 500 by biological filtration with post-treatment and underground effluent disposal.

Experiments documenting the longevity of *Escherichia coli* in comparison to *Salmonella typhosus* were established by Beard (230). He showed that 96% reduction of the typhoid organism occurred after six hours' aeration in activated sludge and up to 99% reduction was obtained when treating the sewage on trickling filters at rates up to 6.6 mgad (152 gal./ft^2/day). At least partial treatment was recommended by Wilson (4747) in South Africa to avoid infection by typhoid or hookworm when using sewage as irrigation for areas where body contact is a possibility. In 1910, strict requirements were developed for the effluent of a sewage plant for Fort Benjamin Harris. It was required that the effluent not be putrescible, must be clear, colorless and practically free of typhoid and other pathogenic germs (3261).

The uses of hypochlorite (107), "oxychloride" (3602), chlorine gas (2554), and high temperature incineration (1458) were among many of the methods used for disinfection purposes. It was noted that an outbreak of poliomyelitis resulted in the recommendation that digested sludge not be used as a fertilizer, even though no direct relation was proved between the methods of sewage disposal and the spread of this disease (3886). Kelly (2425) found that primary and secondary treatment for biological filtration without chlorination did not reduce the frequency of virus isolation. Virucidal effects of chlorine in waste water indicated (539) that less chlorine was required to inactivate phage in settled sewage than in filter effluent, but testing techniques left much to be desired. It was reported (3146) that the activated-sludge plant aerators and the trickling filters were the major source of emission of coliform organisms. However, 50% of the particulate matter emitted was above 5 micron diameter (3146), would be filtered by nasal passages, and would not reach the lungs. In the Biofilter (1158), the high protozoan activity controlled the undesirable bacteria by their activity increasing with increasing load.

Critique

The effectiveness and the limitations of the biological trickling filter as a disease controller are demonstrated in the literature. The aerobic secondary treatment has been shown to be quite useful for the control of enteric, anaerobic, and pathogenic bacteria for many years. Trickling filtration is but one method of providing the aeration. However, indications are that the sorptive capacity of the biofilm for colloidal particles, e.g., pathogens, etc., possesses additional treatment capabilities. For positive control of virus and disease, chlorine or other disinfectants must be used.

It is of interest to note that litigation is presently underway dealing with organic pollution abatement and other violations of waterways. Accusations question the inadequacy of plant designs to provide the required treatment. Additional Government standards and guidelines are introduced dealing with the nutrient content of waste treatment plant effluents. This activity has been intensified considerably from previous years, when storm water sewers were causing the problems in receiving bodies and simple primary treatment was required. In addition to the stream receiving the effluent being contaminated, disease transfer, as exemplified by the epidemics which spread throughout Europe and this country, was a distinct possibility. The purposes of waste treatment should be kept in mind when pointing out the inadequacies of an old plant for nutrient control, but which is still keeping disease from running rampant.

PART III

TRICKLING FILTER RESEARCH AND DEVELOPMENT APPROACHES, ECOLOGY, AND PATENTS

This section first supplies information pertaining to the type of approaches used to develop the current technology of biological trickling filters. The approaches to research and development were divided into areas which were commonly reported in the literature, i.e., laboratory-scale, pilot-scale, and field- or full-scale. Secondly, due to the importance of the biological reactions and relationships, the ecology of the trickling filter is reviewed in some detail. Thirdly, a section on patents is included, as patents represent the end-product of research and development. No critique or comment is made since many of the patents lapsed, and the detail which would be required to review them adequately is beyond the scope of this review.

SECTION XIII

LABORATORY-SCALE INVESTIGATIONS

In this section, laboratory-scale investigations may be defined as bench-top measurements, usually under room temperature and/or controlled conditions, with proper and sufficient analytical equipment readily available. Unless defined otherwise, all experiments described in this section are on the laboratory scale.

Typical of academic studies were those from the University of Newcastle upon Tyne which used laboratory, as well as larger size, biological filters (5608) to determine the ability of isolated biofilm bacteria to metabolize various synthetic sewages. It was concluded that no specific strain of organisms possesses greater purification capacity than that of a heterogeneous population. Brébion (450) described an apparatus which was designed to simulate conventional treatment of sewage by coagulation, mixing, primary sedimentation, activated sludge, biological filtration, secondary sedimentation, and modifications thereof which were used to study the treatment of sulfite waste waters. Concern was expressed by Gameson et al. (1400) on the validity of data obtained on small trickling filters, and therefore twelve replicate systems were maintained simultaneously to determine reliability of the data. Stopler et al. (4236) reported on the design and operation of a glass-column, laboratory filter. Later, Eckenfelder and Cardenas (1084) discussed the selection and operation of laboratory activated-sludge units and percolating filters in conjunction with techniques to be used to establish full-scale design criteria.

Laboratory studies were conveniently used by Nemerow and Armstrong (3165) on the activated-sludge process prior to pilot-scale operations using activated sludge and trickling filters. Brébion and Huriet (452) suggested that the selection of a treatment system was most effective and economical based on results from laboratory and pilot plant conditions. This concept was practiced by Dickerson (956) to determine optimum conditions of treatment for an existing two-stage high-rate biological filtration followed by activated sludge. Alternating double filtration to handle waste treatment in Ventura, California, was shown not to be beneficial, contrary to reported experience, based on laboratory investigations (4266). Studies which would be very difficult on larger scale, such as measurement of data on sub-surface disposal of trickling filter effluents, were made on laboratory soil filters which were dosed under intermittent and continuous conditions (3430).

Detailed functional and practical data were gathered on laboratory filters (4236). Oxygen saturated dilutions of a nutrient source circulated through tubes containing biofilm increased

Preceding page blank

the flow and caused increased turbulence (1775). From this simulation, it was concluded that more turbulence increased the supply of food and oxygen, and, therefore, accelerated the metabolic rate of the total system (1775). Laboratory models of biofilters 165 cm (65 in.) high and 10.5 cm (4.17 in.) diameter were used (2365) to evaluate oxidative processes on biological filters composed of quartzite, gravel, limestone, coke, anthracite, and boiler slag. Experiments with variations of periodicity of dosing in laboratory percolating filters were made (4989) and it was concluded (573) that the maximum interval was eight minutes. Ganczarczyk and Suschka (1404) used laboratory columns 120 cm (47.2 in.) long and 20 cm (7.88 in.) in diameter of zinc plated steel pipe as biolfilters to determine kinetics of aeration by measuring a decrease of sulfite concentration in a synthetic sewage.

Results from experimental studies indicated (3702) that media depth had little effect on the efficiency per cubic yard of medium based on settled sewage flow rate of 220 gal./yd^3/day (8.14 gal./ft^3/day) applied to filters 3, 4, 5, 7-1/2, and 9 feet deep (2.71, 2.04, 1.63, 1.09 and 0.91 gal./ft^2/day, respectively). Balakrishnan (153) found a good correlation between specific surface area of the six-foot deep media and nitrification rates. Stone (4227) experimented with ground water supply, which led to the construction of a potable water treatment plant incorporating a biological trickling filter to remove sulfides. Analytical techniques such as photographic methods were used to study the behavior of water flowing freely down vertical surfaces at Reynolds numbers between 200 and 30,000. The thickness of the liquid layers under varying dosing conditions (250) was thus determined. Neutron scattering techniques were described by Eden et al. (1104) to demonstrate the relationship between weight of film, retention period, and performance.

Rotary tubes were used as laboratory models of biological trickling filters (1402, 1489) in which detailed information on oxidative capacity, radioactive sorption, ecology, and other bio-control factors were obtained. Inclined rotating tubes which develop a biofilm were used by Tomlinson and Snaddon (4429) to determine the critical depth related to nitrification as 0.2 mm (0.08 in.) and evaluate diffusion coefficients. Kornegay and Andrews used a rotating annular ring reactor to develop a mathematical model for biological filtration. The biofilm reached a constant thickness of approximately 200 microns, at which time the shear on the film surface was sufficient to wash the newly formed organisms into the liquid phase (2547).

Gulevich (1621) applied a rotating disc for a laboratory simulation of a trickling filter. The disk presents, mathematically, the simplest surface with regard to mass transfer. This device was well suited for evaluating the relative importance of diffusion using glucose as a nutrient, and it might be of value on more complex compounds. Laboratory and pilot plant experiments to treat phenolic wastes from aircraft maintenance were evaluated by Reid et al. (3547) on rotating drums, biological filtration, and activated sludge. They concluded from these studies that the rotating drum type plant was the best for very high concentrations of phenolic waste.

Mathematical relationships were developed by Howland (2064) using laboratory models of biological trickling filters. Maier (2837) used a flat inclined surface covered with a biofilm to simulate and study the purification of sewage in percolating filters. Mass transfer and growth rate were related to the flow pattern and other biotic factors. Swilley and Atkinson (4276), Kehrberger and Busch (2419), and Busch (548) used laboratory models composed of an inclined plane which was used to describe and analyze trickling filter systems. Filtration simulation by an inclined plane was also reported by Atkinson et al. (100) in the study of the phases of growth of the biofilm related to hydraulic and organic factors. Mathematical studies of reactions in biological filters were proposed (100, 548, 2419). Schulze (3916) and Green et al. (1571) used a vertical laboratory screen simulated filter to develop a relationship between hydraulic and organic load and efficiency, as well as to measure growth rates under controlled temperature conditions.

Contact time on trickling filters was determined by Bloodgood et al. (364) by a laboratory simulation, such as a string of spheres hanging vertically and an inclined plane. The contact time was determined (364) to be inversely proportional to the two-thirds power of the liquid application rate. Sinkoff et al. (4042) also studied the mean retention time on trickling filters and used a simulation consisting of columns packed with spherical media, such as glass and porcelain, of varying sizes.

A thin film aeration reactor was used (4507) to determine that oxygen saturation was reached within two feet of filter depth, using a loading rate equivalent to that of normal practice in biological filtration. Forced ventilation in these experiments did not increase the oxygen uptake. Oxygen consumption was measured and found to be between 60 mg/l and 160 mg/l for sewage supplied by normal atmospheric ventilation. Atkinson and Swilley (101) used laboratory percolating filters to show that suspended solids and dissolved salts reduced the efficiency, and addition of ferric chloride to the influent sharply reduced the removal efficiency. However, the addition of salt to the influent to twelve laboratory percolating filters was observed by Mills and Wheatland (3017) to have little effect upon the total number of scouring organisms present.

The Water Pollution Research Laboratory applied biological filtration and activated-sludge units to determine the treatability of a specific industrial waste and to develop process modifications on existing waste treatment plants (5186). Porter and Dutch (3437) described a laboratory apparatus used to obtain data on plastic biological oxidation media to handle industrial wastes such as phenol or cyanides.

Successful laboratory operation of biological filtration and activated-sludge processes was followed by pilot-scale systems operated in series to handle pulp and paper mill wastes (2661). Brebion (449) in 1958 used 36 porous columns seeded with various fungal cultures which were evaluated for treating dilute sulfite waste waters and the encouraging results suggested that 80% to 90% reduction in BOD could be obtained.

Biological filtration followed by activated-sludge treatment was determined successful (683) and the relationship of temperature and content of hydrogen sulfide on the efficiency of treatment was defined based on experiments on the treatment of fatty acids by covered percolating filters. Laboratory and pilot plant experiments by Christ (684) supported these findings and also found that waste waters from the manufacture of fatty acids could be treated to 90% organic removal.

Kucharski and Krygielowa (2582) investigated the treatment of phenol-formaldehyde plant waste on laboratory filters and the successful operation provided input for larger scale testing to confirm that the phenolic concentrations of the waste waters were reduced from 200 mg/l to 1-2 mg/l. Laboratory filters were used by Zdybiewska (4852, 4854) in Poland, to determine the feasibility of biological purification of phenol wastes, and to define the procedure of microorganism acclimation. Similarly, laboratory and full-scale percolating filters were constructed at Knostrop Sewage Works by the Joint Research Committee of the Gas Council of the University of Leeds to study the biological treatment of mixtures of sewage and trade waste fractions of problem effluents (5606). Laboratory-scale studies on oil refinery waste waters were reported by Luchter (2775) who evaluated slag, coke and calcium carbonate as filter media, finding the last one to be unsatisfactory. The Magdeburg Process of direct biological treatment of spent gas liquor without sewage was studied under laboratory conditions (3193). Many laboratory treatability studies, e.g., Michail and Popescu (2998), developed methods for the treatment of waste waters containing tar and phenols discharged from coal gasification plants.

Patil et al. (3310) stated that it was originally proposed to carry out pilot-scale studies on the treatment of synthetic drug wastes by biological filtration, but the cost of preparing a synthetic waste to simulate the composition of the actual waste effluent required preliminary experiments. The results of these studies indicated that biological filtration had little effect in reducing the oxygen demand and considerable savings were made. Both trickling filters and activated sludge were effective in reducing the BOD of sugar refinery wastes (3203), as was demonstrated, initially, by laboratory and, later, by pilot-scale operation.

Industrial wastes such as that from the tanning industry were evaluated (2089) using laboratory and pilot-scale studies, from which it was determined that a rate of 70 gal./yd^3/day of sewage containing 30 mg/l trivalent chromium could be applied to the filters. Approximate toxic levels of metal finishing wastes were established, initially, by laboratory operation (3979), and later expanded to pilot-scale operations. Safe limits of treatment of metal plating wastes were reported by Kittrell (2502) based on experimentation with metal plating wastes, such as cyanide. During additional work, a pair of insulated laboratory-scale filters equipped with sampling ports of various depths was used by Ware (4606) to determine the effect of temperature on the biological destruction of cyanide waste.

Critique

A significant portion of the literature contained references dealing specifically with the use of laboratory-scale operations simulating various facets of the biological trickling filter processes. Many of the studies were undertaken using laboratory-scale operations to facilitate control of variables, such as the influent stream, temperature, humidity, invading organisms, and other factors which normally affect the process. As more data were made available and the tendency was established to develop rational formula for design purposes, several investigators found it convenient, economical and highly desirable to use laboratory-scale filtration systems.

From the viewpoint of research, the more well-defined the system the more accurate and applicable are the data generated. From the practical standpoint, the use of a smaller system to investigate specific problems has been shown to be efficient, economical, and, with proper interpretations, reliable. The proper interpretation is a point not to be minimized, since the temptation is great to immediately extrapolate data gathered under well-defined and controlled conditions at the liters per day scale to predict responses for large waste treatment facilities handling millions of gallons of waste per day. Techniques have been evolved, however, in which information generated from this scale operation may be used to make these full-scale predictions. If time is the limiting factor for the development of a well-founded waste treatment system, laboratory-scale investigations, if properly designed, operated, and interpreted, may produce data from which recommendations may be made with more justification than simply opinion.

It appears from the review of this literature that the most common procedure has been to use laboratory-scale simulation to develop ranges of performance and design criteria from which pilot-scale operations may be developed. For a large installation involving significant capital outlay, this procedure obviously has merit. However, as larger quantities of data become available and further basic understanding of the processes is developed and disseminated, it is not beyond comprehension to consider that laboratory-scale simulation (not necessarily in the form of miniaturized plants) could be used extensively to measure specific reactions and phenomena required for design at various points in the waste treatment plant. These laboratory data would be applied directly to establish design relationships for full-scale sizing and operation. Furthermore, by computerizing the pertinent available data from the literature, the probability of eliminating the laboratory or even pilot plant step in the development of a process for the purification of waste waters could become a reality.

SECTION XIV

PILOT-SCALE INVESTIGATIONS

Pilot-scale investigations may be considered as studies at a large enough scale to be representative of phenomena experienced by the prototype, yet be small enough to have some control and allow changes to be made economically. Stenburg et al. (4206), in a general review of wastewater treatment approaches, outlined several pilot plant and full-scale studies, and considered pilot plants as the modern method to wastewater treatment. Procedures for selecting industrial waste treatment processes were recommended by Stack et al. (4158), involving local requirements, economic considerations, plausible alternative treatment systems, with the final decisions based on pilot scale operational data. As a consulting engineer, Higgins stressed (1935) the value of pilot plant data used in the design of waste treatment plants, specifically those employing plastic media trickling filters. Burgess et al. (536) determined the reliability of measurements for testing treatment efficiency, and loading was evaluated, based on pilot deep-bed percolating filters. The results substantiated the Velz basic law. Statistical methods used to design experiments and analyze data obtained from pilot plants were emphasized by Blarigan and Lamb (352), and observations were made at as many combinations of the different levels of each variable as possible, rather than the usual method of altering only one variable at a time. Typical of pilot plant studies was that of Ingram and Edwards (2227), where an 18-foot deep experimental filter was divided into four sections and the ecological population and stratification in each section of the filter bed determined.

Sponsoring agencies, such as the New Brunswick Research and Productivity Council (5330), were active in the development of pilot- and full-scale trials employing various methods of treatment, such as percolating filters with plastic media to treat trade wastes. With the development of new biological trickling filter media, pilot plants became valuable in determining design criteria, such as contact time and efficiency in removing specific organic pollutants (154). Hawkes and Jenkins (1820) studied the comparative behavior of various media trickling filters and the accuracy of the data gathered from these studies, e.g., Bruce et al. (507). Studies on specific media to justify their use were frequently performed, such as the one by Althaus (60), who used the bullrush Scirpus lacustris in a pilot plant contact aeration device and demonstrated a 95.7% reduction in BOD. Another example was that reported by Truesdale et al. (4463), in which eight rectangular filters containing various inorganic media were studied to determine the effect of the media on the behavior of the percolating filter.

Operational changes have been demonstrated by pilot-scale testing of existing waste treatment systems. For example, Lumb (5530) reported that the capacity of an existing waste treatment plant was increased by a 1:1 dilution of the sedimentation tank effluent with that from aeration tanks before biological filtration. In this way, the load on the filter could be at least doubled, and a superior effluent produced.

During pilot plant studies, Barth et al. (204) found that the inability to control process variables effectively in trickling filter treatment made more efficient nitrogen removal by modifications of existing structures more unlikely and favored the use of activated sludge. Pilot plant studies were used to determine required facilities for plant expansion and to define criteria from which a full-scale unit was designed, e.g., plastic media pilot plant used to remove a minimum of 50% BOD applied at 350 lb/1,000 ft^3/day (4086). Oliver and Hall (3241) and Culver (839) also used pilot plants to develop data to determine the modifications required to existing facilities to improve the effluent to conform with standards. Additional techniques, such as bacteriological analyses, have been used by Sima (4029) to evaluate the performance of pilot scale biological filtration plants. A neutron scattering technique to determine the amount of biological film in a pilot scale percolating filter was described (1782) and the results from this method were reported and discussed. Tertiary treatment of biological filtration effluent, such as deep well injection with various forms of chemical and mechanical treatment, has been studied by Hennessy et al. (1881) in pilot scale operations.

Petru (3342) and Bayley and Downing (226) determined the effect of temperature on the flow of air through percolating filters based on pilot-scale filters operated over a significant period of time. They concluded that cooling was affected not so much by the external temperature as by factors affecting aeration and by the characteristics of the individual filter, such as the ratio of diameter to depth (3342). The most important factor is the temperature of the applied sewage, but the exchange of heat with air, especially near the surface, and the production of heat by biological oxidation are also significant (226).

Specific problems, such as to determine that recirculation of humus to the influent reduced the amount of inorganic coagulants required for efficient treatment of aircraft cleaning wastes, have been attacked (30) on pilot plant systems. Pilot-scale determinations to verify laboratory results of retention time tests were reported by Sheikh (3981) to be necessary in the logical progression of the application of the developed information to full-scale field design.

The effect of digester supernatant was investigated by Sorrels and Zeller (4113) on pilot plant experiments with percolating filters. They observed that the primary filter appeared to act mainly by flocculation and the secondary filter by oxidation of carbon and nitrogen. These pilot plant operations demonstrated safely and economically that digestor supernatant liquor was amenable to biological filtration at loadings up to 23 lb of BOD/1,000 ft^3/day on primary filters and up to 92 lb of BOD/1,000 ft^3/day on secondary filters. The effect of hydraulic loading and depth on percent BOD reduction was measured (4) on an 11-foot high pilot filter, 5-foot diameter, and it was concluded that the highest BOD removal per 1,000 ft^3 of filter media occurred at the 3-foot depth with a hydraulic loading of 30 mgad (690 gal./ft^2/day).

Pilot plants have been frequently used to obtain design data for specific industrial wastes. Experiments were used by McGaughey (2909) to determine the biological treatability of "hard" and "soft" detergents and the data compared closely with that from full-scale operating waste treatment plants of similar types. Husmann et al. (2153) also evaluated, as did many others, the biodegradability of soft detergents in laboratory-, pilot-, and full-scale activated sludge and percolating filter plants, which indicated that 80% of the detergent could be removed by either process. Lawrence (2642) determined the effectiveness of biological filtration in the removal of low level radioisotopes from waste waters on a pilot plant scale.

According to the results of pilot plant operations, activated sludge was more effective than biological filtration in treating tannery waste waters (3923). For textile wastes, Snyder (4094) found the effectiveness of plastic media trickling filters sufficient to design a full-scale treatment plant and assure a BOD reduction of 60 to 70%. The effect of pH on trickling filter performance was determined by Walter (4592) by pilot plant studies on combined sewage and textile waste. He found that pH values above 11 or 12 reduced BOD removal rates. Three pilot plants were used simultaneously by Munteanu (3124) to determine design parameters for full-scale plants to treat waste waters from the manufacture of cellulose and viscose artifical fibers, thereby reducing observation time and increasing flexibility. A pilot plant used in Russia to determine the operating techniques to treat waste from an artificial fiber plant was also designed to operate under extremely flexible conditions (1393).

Noble et al. (3193) in 1964 summarized the activities of the Gas Council since 1951, which sponsored pilot-scale experimentation on activated-sludge and biological filtration processes to treat gas liquors (2296). Oil refinery (3205) phenolic wastes were tested under pilot plant conditions to demonstrate the applicability of biological filtration and activated sludge processes. It was concluded that the shock-resistant biological filtration process was preferred, and a full-scale plant was constructed. Laboratory experiments (3018) indicated that certain pesticides were amenable to biological treatment, and pilot plants, with plastic media filters and activated-sludge systems, were operated to determine design criteria. It was determined (3018) that a full-scale activated-sludge plant would reduce the phenol concentration by 99% and the BOD by 90 to 95%. Black and Fairall (342) reviewed in 1963 the pilot plants for developing operating data for the biological treatment or organic waste waters by activated-sludge and percolating filter plants. Pilot plant operations determined that the activated-sludge process was more suitable (5621) than percolating filters to treat chemical plant effluents.

Ratliff (3508) described the advantages of pilot plant studies on a paper mill effluent to consider the activated-sludge process and biological filtration. Neither method was satisfactory, and the effluent from a circulating lagoon was treated by biological filtration to produce a satisfactory treatment. A pilot plant designed to treat 100 m^3/day (26,400 gal./day) of pulp mill waste was operated by Gânczarczyk (1403); however, Schmidt (3873) found that dual treatment by activated sludge and biological filtration provided a flexible waste treatment facility, reducing the BOD by 80%. Similarly Nowacki and Pilotek (3206, 3207) used a pilot plant to treat the waste waters from the manufacture of kraft pulp which was designed to include physico-chemical treatment followed by biological treatment. After a twelve-month investigation on pilot plant-scale trickling filters, Richey (3593) concluded that chipboard wastes were removed effectively on a low rate trickling filter with the effluent satisfactory for discharge. It was concluded (2993) that at all hydraulic loadings from 1 gal./min (1,440 gal./day) to 7 gal./min (10,000 gal./day) the BOD removals exceeded 50% on a plastic medium in a pilot trickling filter with paper mill effluent, and that supplemental nutrient such as anhydrous ammonia would be the most economical. Minch et al. (3024) and Ruus (3795) used pilot plant scale plastic media trickling filters for the treatment of paper mill effluent and indicated that the percent BOD and COD removal decreased significantly with increased hydraulic loads.

Norgaard et al. (3200) described pilot plant studies to establish design parameters for canning wastes which included (a) anaerobic digestion followed by either activated-sludge process or high rate biological filtration, (b) primary sedimentation followed by either single- or two-stage high rate biological filtration, and (c) the activated-sludge process both with and without primary sedimentation. Based on pilot studies, cost estimates for alternative plans and expected removals were developed and presented. Food processing wastes, such as that described by Leete and coworkers (2669), have often been characterized by their performance on pilot-scale operations used to develop design criteria, e.g., a recirculation ratio of about 4.5:1 on a pea cannery waste was required to produce an overall BOD reduction of 78.8 percent. Chalmers (647) found from pilot plant studies of activated sludge and trickling filters treating the effluent from a complex food manufacturing and coffee processing plant that the waste was more economically treated by physical means. Sugar refinery effluent was treated (4006) in a pilot plant by a high-rate percolating filter to give a 70% reduction, which increased to 92 to 95% after stabilization of the treated effluent in a 72-hour detention holding tank. Pilot-scale evaluations were made by Grau (1544), in 1961, on the effect of screening fruit and vegetable wastes prior to biological filtration with and without recirculation. He concluded that best results were obtained without recirculation and a pH value of 6.6 to 6.9. Adverse effects of recirculation are attributed to the lack of nutrients. The temperature of air or waste water had little effect.

Hirlinger and Gross (1959) found from pilot plant studies on biological filtration that waste waters from a packing house, after pretreatment, were treated satisfactorily if care was taken to ensure a constant flow over the filter. Tests on pilot-scale anaerobic digestion plants for treating slaughterhouse wastes were used by Silvester (4027) as input so that a full-scale plant was constructed with the effluent discharged on existing percolating filters with no expected problems. Pilot plant studies on the treatment of dairy waste waters were carried out by Svoboda and coworkers (4272), who determined that the optimal BOD loading was 600 to 800 g/m^3/day (37-50 lb BOD/1,000 ft^3/day). Other investigators, such as Tidswell (4389), found from pilot scale treatment studies that brewery wastes could be treated at 75 gal./yd^3/day (2,775 gal. of sewage/1,000 ft^3/day) to produce satisfactory effluents.

Critique

Pilot-scale operations were applied to several areas of research and development for biological trickling filters. The use of pilot-scale operations is a logical step between laboratory and plant-scale operations, and investigators were able to evaluate laboratory results and theories without investing large sums of money and capital equipment. Pilot plants have the flexibility that, once constructed, changes could be made without causing major design problems.

It should be emphasized that a major factor in the credibility of the results from pilot plant operation is the condition under which it operates. The example which was most common was that of pilot plant operations to develop design criteria for a specific trade waste. Pilot plants of this type were established, usually, in the geographical area where a prototype plant would be built and were subjected to the waste in question for a significant period of time. Once the investigator was assured that the pilot system had experienced the perturbations that the prototype system would experience, the next task was that of correlating this information to be used for prototype applications. On occasion, it was reported that the operation of a specific pilot plant was a failure and that the waste was not removed by the filter system. This, by definition of the use of pilot plants, was not a failure because it saved the owner considerable expense by not constructing the prototype plant based on the evidence at hand, but only the costs for the construction of the pilot plant.

Several companies have found it a necessary step in the development of a market to provide their particular component for pilot plant testing under the conditions which would be expected after construction of the full-scale plant. An unfortunate by-product of pending legislation and the conservative approach of using pilot plants for an extended period of time has been, in essence, a stalling action for pollution abatement. Considerable data are available on the operation and maintenance of biological trickling filters under many conditions treating many wastes. These data, when supplemented with limited data of laboratory and pilot-scale origin, would appear to provide sufficient information so that full-scale design and construction would be more readily pursued.

It is unfortunate, but understandable, that pilot plant operations have not been used extensively for the development of rational formulation describing the performance of the biological filtration process. It would seem logical, following the conservative lines used for construction of new facilities, that mathematical models developed in the laboratory should be exhaustively evaluated at pilot plant-scale and modifications of the model be made to adjust any disagreements. It should be noted, however, that the use of pilot plant-scale investigations to develop design criteria does not need to be perpetuated, if basic understanding of the processes involved is established and agreed upon at any scale of testing.

SECTION XV

FIELD- AND FULL-SCALE INVESTIGATIONS

Studies accomplished in the field and at prototype scale have been regarded by many as the real "acid test" of a concept, e.g., investigators such as Hall (1654) developed information at pilot scale, but stress that proof must be given at full-scale conditions. A good example of field studies was reported by Benzie et al. (273), who evaluated climatic conditions and loading factors on the performance of percolating filters. The operational results of seventeen full-scale installations in Michigan were compared and factors of filter efficiency, BOD loading, recirculation, and ventilation rates were evaluated.

Observations of field-operated systems have been used by Otto (3259) to predict expected results of process modifications that often result in considerable savings of time, money, and damage to the environment. Field evaluations of the performance of existing plants were noted (4959) as useful to determine when reconstruction was necessary and to indicate the type of plant which should be built. Ecological investigations were conducted under field conditions by Chaudhuri (663) to establish microbial population identity and occurrences in the several unit processes of the treatment plant. However, most industrial waste surveys involved, in addition to published information and laboratory investigations, data gathered from the field to assess the volume and strength of the waste (3436). A field survey of municipal waste treatment plants was made (203) to determine the effect of metals on sewage treatment, which confirmed pilot-plant studies that heavy metals in concentrations of 1 to 9 mg/1 caused no serious reduction in efficiency of either aerobic or anaerobic waste treatment processes. Barth et al. (204) studied five biological treatment plants in Ohio to determine the efficiency of nitrogen removal by municipal wastewater treatment plants. From these field studies they concluded that where nitrification occurred denitrification followed, suggesting an anaerobic process was possible for the removal of nitrogen from the effluent.

Field comparisons on activated-sludge and biological filtration systems for the removal of various pollutants, such as viruses (2243), gave valuable information for system modifications. In this case, chlorination of effluent to inactivate the virus would be acceptable for design. Valuable comparison data of cost and effectiveness of activated-sludge and trickling filter plants operated in parallel were reported by Dye (1055), based on a million gallons of sewage per day operation. Field evaluations have often been used for full-scale installations of package plants (5118) where units were presized, shipped to the job site, and evaluated. Kehr and Möhle (2417) conducted systematic experiments at various plants treating highly polluted waste waters to assess the efficiency of two-stage biological treatment, namely, the activated-sludge process followed by percolating filters. This procedure was typical of field-gathered information which was used for future design and from which actual operating procedures were defined.

Typical procedures required for a large capital investment existing facility to be updated were related by Oliver and Hall (3241). They obtained information on grading and depth of medium satisfactory for a full-scale filter from a pilot-scale operation in conjunction with existing high-rate filtration with recirculation. Expected performance of a modified plant was verified by Wilson and Harrison (4757) using laboratory- and full-scale studies, and they concluded that the efficiency of percolating filters was improved by recirculation of the effluent. The improvement was explained to be due to the effects of recirculation of organic matter which more than compensated for the reduction of retention periods. Laboratory- and full-scale experiments were used by Seidel and Bauman (3957) to determine whether preliminary aeration had a beneficial effect on biological filtration. The preliminary treatment was advantageous when plain sedimentation was the least effective and it was demonstrated on a plant-scale that aeration for 45 minutes, followed by sedimentation for one hour, gave consistently better results than plain sedimentation alone for two hours. Based on the results of prolonged full-scale tests of percolating filters, the design of a system to handle 90 mgd (207 gal./ft^2/day) and 1,000 pounds of BOD/acre/day (23 lb of BOD/1,000 ft^3/day), as well as several other modifications to the existing Dallas, Texas, waste treatment plants, was described by Graeser (1530). Kastler (2383) reported on field investigations of enclosing a trickling filter in a concrete and fiberglas structure which resulted in efficient treatment and minimum maintenance with no icing occurring during periods of sub-zero temperatures at Northwood, Iowa. The alternating double filtration technique was developed under full-scale operating conditions, but it was based on the results of pilot-scale experiences (3251) prior to full-scale construction.

A mathematical formulation of the biological oxidation process had been proposed by McCabe (2895), which fitted the laboratory and field data. Sheikh (3981) tied together several studies on retention time using laboratory-, pilot-, and full-scale experimentation with radioactive tracers. He stressed that the performance data obtained under pilot plant conditions were applicable to field-scale installations only if the two filters were operating under the same conditions (depth, medium and hydraulic loading). Field installations, operated in conjunction with laboratory and pilot plant studies to verify operational variables and aid in this statistical interpretation, as in the case with single- and two-stage trickling filter plants, were studied in detail by Blarigan and Lamb (352).

Pilot plant and field data were used by Germain (1460) to develop an equation for predicting the performance of percolating filters containing plastic media for treating domestic sewage containing only a small amount of industrial wastes, from which further evaluations were to be made. The National Research Council (5590) used the field observations from several hundred sewage treatment plants to develop the NRC formulation. Stanbridge (4175) carried out large-scale experiments on sewage works to determine the effect of periodicity of dosing on the performance of the percolating filters. He concluded that controlling the accumulation of film in low frequency dosing enabled high-quality effluents to be produced throughout the year, while the winter performance of filter treated differently deteriorated because of ponding.

General papers, such as that outlined by Albertson (27), provided information on handling industrial waste based on field investigations. Often the problem had been previously solved and field studies were used to test their effectiveness so that designed modifications and operations in the future would correct the errors in past designs. Quite often field investigations were in the form of plant trials such as reported by Petru (3341), who evaluated a biological filtration plant for treating flax retting waste. An assessment of the pollution load is a necessary requirement for a trade waste design, as illustrated by Wheatland and Borne (4697) while investigating waste disposal at dairy farms. Occasionally, reports were published which used laboratory-scale devices in conjunction with field testing to determine the most effective treatment system to be designed, as was the case of treatment of waste from a hydrolysis plant carried out on an industrial filter and on a glass model 1.5 meters (59 in.) high (1034). Conclusions were reached based on the glass model and correlated with the performance of the industrial filter such that the minimum height and contact time were established. Gerlich (1459) reported that the operation of full-scale plastic media filters for Cedar Rapids, Iowa, for treating sanitary and meat packing wastes was better than expected from the pilot model.

Pilot- and full-scale operation of plastic media biological filtration towers was reported by Minch et al. (3024). The operation of the treatment plant showed that the trickling filters are capable of withstanding shock loads and severe hydraulic overloads while treating pulp and paper mill waste. Design and operational requirements were developed to justify an installation of this type and a full-scale plant was constructed. Pilot studies verified by field studies were used by Chipperfield (681) to indicate the usefulness of plastic medium trickling filters for single- and multi-stage plants treating various industrial wastes.

Large scale experiments have been frequently made by British investigators to determine the treatability of various trade wastes, such as reported by Blackburn and Tomlinson (345) in 1955 for the treatment of gas works liquor with biological trickling filters. Field tests were performed (4285) to establish an economical process by which combined domestic and phenolic waste waters could be treated using treatment plant elements such as settling tanks, rotating distributor, percolating filters, and recirculation. However, laboratory-, pilot-, and full-scale studies were used for the treatment of gas works liquor by Drabek (1024), from which it was concluded that with careful operation the percolating filters could achieve complete removal of the phenols from waste waters.

Following pilot plant studies, field studies were used to considerable advantage during the detergent degradability studies of the early sixties, whereby effluent samples from several existing trickling filter and activated-sludge plants were taken to determine the degradability of hard and soft detergents (2909). It was concluded that linear alkylsulfonate-type of detergent ("soft") is more readily degraded than the "hard" type and where secondary treatment is provided it should reduce foaming in the receiving waters. Typical of this type of work was that by Jendreyko and coworkers (2271, 2272), who made full-scale investigations of detergent biodegradability in trickling filters and activated sludge by adding known quantities of detergent to waste waters and measuring the percent decomposition under field conditions. Commercial detergents were tested by Husmann et al. (2153) in laboratory-, pilot-, and full-scale biological filtration and activated-sludge plant which indicated that 80% or more of the soft detergents was decomposed and high concentrations did not interfere with the performance of treatment plants. Kumke and Renn (2590) specifically used a low-rate percolating filter which served an institutional home to determine the biodegradability of linear alkyl sulfonate (LAS) detergents and concluded from these field studies that the detergent was removed as efficiently as naturally occurring organic materials.

Critique

The major contribution of the field and full-scale testing program, as derived from the literature, was the high level of credibility given the data generated. These data, which were obtained under actual operating conditions, reflected all of the variables of the environment plus sampling and interpretation. When a clear relationship was discovered among the variables, the information became extremely valuable. Theories which were developed under laboratory and pilot plant conditions and verified by full-scale testing have been well accepted as representing the phenomena.

It should be noted that the expenses involved in developing full-scale data are much higher than those of other scale operations. Occasionally, data have been shown to be valueless due to improper sample handling and delayed analytical testing. Because of the many coexisting variables, basic understanding and definition of the process mechanism are extremely difficult under full-scale testing conditions.

Full-scale testing and measurement have been used to advantage in the development of modifications to existing waste treatment facilities. Industrial waste surveys before and after the construction of a waste treatment plant have been used for many years to develop criteria for full-scale design and operation. The conservative approaches of limited laboratory investigations, extensive pilot-scale investigations, followed by full-scale construction and operation are extremely valuable for the development of complex waste-treatment facilities. As may be inferred from the bibliography, full-scale testing occupied a significant portion of the literature. The references reviewed here are indicative of only a small fraction of this material, but cover, in general, the performance evaluation, ecological investigation, process modification, and similar type studies.

SECTION XVI

ECOLOGY

The trickling filter presents three elements which determine its function and its population:

1) A trickling filter is designed to contain a ventilated surface to which is applied a polluted substrate containing required minerals and materials which microorganisms can metabolize with net production of energy for growth or sufficient energy to maintain the existing population.

2) The filter is always fed from the top and designed to collect effluent at the bottom. The feeding may be continuous or intermittent and the feed may include recycled liquid and solids which have previously been passed over the filter.

3) In general a trickling filter is followed by a secondary settling device which removes material converted to settleable solids by the combined forces of synthesis and/or biocoagulation in the filter.

The trickling filter is always used as a device for biological oxidation, but a substantial portion of the purification made possible by the filter is usually accomplished in the sedimentation system which follows the filter.

Perhaps the most comprehensive descriptions of the populations found in trickling filters was presented by Cooke (779). Cooke's listing of organisms reported to be found in trickling filter populations is presented as Table VI, and is given on the following pages.

Cooke (775) analyzed the interactions of the complex populations found in trickling filters in some detail and commented on their relationship to percolating filter beds, e.g., "binding" organisms which formed the biofilm, "free living" organisms which fed on the bacteria, and "scouring organisms" which fed directly on the biofilm and sewage solids and gave additional information on techniques and growth characteristics.

Algae growing on the surface of trickling filters are usually an inconsequential element of the population, limited to illuminated surfaces, although the organisms have been charged with responsibility for bed clogging (1826). Covered filters and filters with very limited illuminated surface are at least as effective for treatment as are open illuminated filters. Algal organisms on filters are clearly tolerant of organic material and high levels of carbon dioxide (779).

Preceding page blank

Table 6

Composite List of Trickling Filter Organisms - Cooke (779)

(Genera in major groups listed alphabetically
regardless of importance or systematics)

- Schizomycetes (bacteria)
  - Sphaerotilus natans
  - Zoogloea ramigera
  - Many unidentified species

- Cyanophyceae (Blue Green Algae)
  - Amphithrix janthina
  - Anacystis montana
  - Oscillatoria limosa
  - Phormidium uncinatum
  - Pleurocapsa sp.

- Eumycophyta (Fungi)
  - Absidia corymbifera
    - cylindrospora
  - Allescheria boydii
  - Alternaria tenuis
  - Ascodesmis microscopicum
  - Aspergillus spp.
    - candidus
    - clavatus
    - flavipes
    - flavus
    - fumigatus
    - niger
    - ochraceous
    - sydowii
    - terreus
    - ustus
    - versicolor
    - wentii
  - Cephalosporium spp.
  - Chaetomium globosum
  - Cladosporium cladosporioides
  - Coniothyrium spp.
    - fuckelii
  - Dematiaceae spp.
  - Epicoccum nigrum
  - Fusarium spp.
    - aquaeductuum
    - oxysporum
    - roseum
    - solani
  - Geotrichum candidum
  - Gliocladium roseum
  - Gliomastix convoluta
  - Leptomitus lacteus
  - Margarinomyces heteromorphum
  - Memnoniella echinata
  - Monilia sitophila
  - Moniliaceae spp.
  - Mucor sp.
    - fragilis
    - plumbeus
    - racemosus
    - saturninus
  - Myrothecium verrucaria
  - Paecilomyces varioti
  - Penicillium spp.
    - brevi-compactum
    - chrysogenum
    - clavigerum
    - cyclopium
    - digitatum
    - expansum
    - funiculosum
    - herquei
    - implicatum
    - janthinellum
    - lilacinum
    - ? luteum
    - martensii
    - nigricans
    - ochro-chloron
    - oxalicum
    - palitans
    - piscarium
    - purpureogenum
    - roquefortii
    - stipitatum
    - variabile
    - velutinum
    - vermiculatum
  - Phoma spp.
  - Pullularia pullulans

Table 6 (Cont'd)

Penicillium spp. (Cont'd)
- Rhizopus spp.
  - arrhizus
  - nigricans
  - rhizopodiformis
- Rhodotorula spp.
- Sphaeronema spinella
- Sporotrichum pruinosum
- Stachybotrys atra
- Stemphyllium consortiale
- Subbaromyces splendens
- Syncephalastrum racemosum
- Trichoderma viride
- Trichothecium roseum
- Verticillium spp.
  - lateritium
- White yeasts

Chrysophyceae (Diatoms)
- Nitzschia palea

Chlorophyceae (Green Algae)
- Aeronema polymorphum
- Characium sp.
- Chlorella vulgaris
- Chlorococcum humicola
- Microthamnion kuetzingianum
- Richteriella sp.
- Stigeoclonium nanum
- Ulothrix tenuissima

Bryophyta--Musci (Mosses)
- Leptodictyum riparium

Protozoa
- Sarcodina (Amoeboid organisms)
  - Actinophrys sol
  - Actinosphaerium eichhornii
  - Amoeba proteus
    - radiosa
    - verrucosa
    - villosa
  - Arcella dentata
    - vulgaris
  - Centropyxis aculeata
  - Chlamydophrys stercorea
  - Cochliopodium bilimbosa
  - Difflugia pyriformis
  - Distigamoeba gruberi
  - Euglypha alveolata
  - Hartmanella hyalina

Protozoa (Cont'd)
- Pomphagus nutabilis
- Protamoeba primitiva
- Trinema lineare
- Vahlkampfia albida
  - guttula
  - limax

Mastigophora (flagellates)
- Anthophysa vegetans
- Bodo caudatus
  - lens
  - mutabilis
- Cercobodo sp.
  - longicaudata
  - ovatis
- Distigma proteus
- Euglena sp.
- Heteronema sp.
- Mastigamoeba sp.
- Monas sp.
- Notosolenus sp.
- Oicomonas socialis
- Peranema trichophora
- Tetramitus sp.
- Trepmonas agilis
- "Many small flagellates"

Infusoria (Ciliates)
- Amphileptus sp.
- Amphisia sp.
- Aspidisca sp.
- Blepharisma sp.
- Carchesium sp.
- Chilodon sp.
  - cucullus
- Cinecochilum margaritaceum
- Colpidium sp.
  - striatum
- Colpoda sp.
  - inflata
- Cyclidium sp.
  - glaucoma
- Euplotes sp.
  - sharon
- Glaucoma sp.
  - scintilans
- Halteria sp.
- Holophrya sp.
- Lembus sp.
- Lionotopsis sp.
- Lionotus sp.
  - fascicola

Table 6 (Cont'd)

- Infusoria (Ciliates (Cont'd)
  - Loxodes sp.
  - Loxophyllum sp.
  - Macrymaria sp.
  - Metopus sp.
  - Microthorax sp.
  - Nassula sp.
  - Opercularia sp.
  - Oxytrichia sp.
    - pellionella
  - Paramoecium sp.
    - caudatum
  - Pleuronema sp.
    - chrysalis
  - Pleurotricha lanceolata
  - Podophrya sp.
  - Prorodon sp.
    - teres
  - Spirostonum sp.
  - Stentor sp.
  - Stylonichia sp.
    - pustulata
  - Uroleptus sp.
  - Uronema sp.
    - marina
  - Vorticella sp.

- Metazoa
  - Turbellaria (Flat worms)
    - Stenostomum leucopus
  - Rotatoria (Rotifers)
    - Euchlanis dilatata
    - Philodina roseola
    - Rotifer vulgaris
  - Nematoda (Nematode worms)
    - Diplogaster strictus
    - Diploscapter coronata
    - Dorylaimus saprophilus
    - Rhabdites sp.
  - Gastrotricha (Gastrotrich worms)
    - Chaetonotus sp.
  - Oligochaeta (Round worms)
    - Aeolosoma hemprichi
    - Dero limosa
    - Limnodrilus sp.
    - Lumbricillus lineatus
    - Lumbricus rubellus
    - Pristina sp.
      - longiseta
    - Tubifex sp.

- Metazoa (Cont'd)
  - Polychaeta (Polychaete worms)
    - Polychaeta sp.
  - Crustacea
    - Cyclops sp.

- Mollusca
  - Lymnaea humilis modicella
  - Physa anatina
    - cubensis
    - halei
    - integra
- Tartigrada
  - Macrobiotus sp.
- Arachnida
  - Torrenticula anomala
- Insecta
  - Cercyon fimbriatus
  - Diploneura cornuta
  - Leptocera fontinalis
  - Limonia simulans concinna
  - Psychoda alternata
  - Scatella paludum
    - stagnalis

As a short term retention device the trickling filter would not be expected to be an effective reduction device for pathogenic microorganisms. This is indeed the case. Thus, there are reports of limited reduction in the numbers of Sal. typhosa, Sal. paratyphi, Myco. tuberculosis (43, 230, 2317, 2358, 3847). This is true also of pathogenic protozoa such as Entamoeba histolytica (812, 2552, 4829).

When loaded heavily with carbonaceous material, nitrification in a trickling filter may be absent or nominal. However, the trickling filter when loaded lightly usually does some nitrification. Applied to secondary effluent, the trickling filter has been found to nitrify ammonia effectively in studies now pending at The Dow Chemical Company.

Much of the early study of trickling filter populations was aimed at the control of filter flies. These nuisance organisms were controlled by flooding, chlorination, various pesticides, etc. (620, 1228, 1723, 1816, 1823, 1824, 1825, 1829, 2731, 2740, 3931, 4410). The filter fly persists as a nuisance where low rate filters are used. However, high rate filters tend to have little fly associated difficulty, except where feed application is very irregular.

The "ponded" filter occurs when strong wastes are applied at low hydraulic rates (in terms of surface loading). These difficulties are related to excessive amounts of growth which clog rock filters and may be controlled by higher flow rates to keep surfaces flushed.

The "sloughing" of the low rate trickling filter is a key to its continuing effectiveness. The continuing presence of an effective grazing population is believed to be needed in order to prevent excessive build-up of attached slimes. The use of insecticides, for instance, has been reported to have been followed by "ponding" on occasion (1817, 1821). Relatively large losses or releases of attached slimes may occur during periods of high activity by worms or insect larvae so that there may be either build-up or unloading of slimes and retained sludges by trickling filters.

Since filter slimes can receive oxygen only at their free surface, a thick slime may have a definitely anaerobic interior and sulfur reducing bacteria have been isolated from trickling filter slimes (3665). Under such circumstances filters can develop odors, and conceivably sloughing can occur as the result of gas generation in the interior of the slimes. Sloughing occurs very frequently after temperature changes in the spring and fall and has been attributed to increased activity by worms and/or insect larvae.

The similarities and differences of the trickling filters and activated sludges perhaps are worth some comment.

1) Because of the short retention time, trickling filters show a somewhat greater resistance to various types of insult than do activated sludge systems. This desirable facet may also be related to lower adsorption capacity.

2) The trickling filter population in large part remains attached to the filter. Accordingly, the age of the total biota is older than that of activated sludge, even though surface slime may have a very low age in high rate filters.

3) Whereas thready fungal or bacterial growth may greatly impair activated sludge by causing reduced separation efficiency in secondary settlers, such growth is quite acceptable in trickling filters.

4) The demands on the operator of the trickling filter are low, and keeping mechanical devices used for distribution working well is the larger part of continuing maintenance. Activated sludge plants present more need for continuing skilled operation and decisions.

5) Hold-up time in the trickler is low compared to the aeration times used in the activated sludge process and overall treatment efficiencies, in terms of "BOD" removal will tend to be lower.

6) The slime or biological population of a trickling filter at any given time consists largely of attached material as compared to the suspended and moving biological floc of an activated sludge system. Accordingly, the waste moves over and past the trickling filter slime, whereas the sludge floc moves with the "mixed liquor." In consequence, there is more opportunity for qualitative biological differences in different portions of the trickling filter as compared to an activated sludge unit.

Critique

The trickling filter is based on the metabolism of attached bacteria and fungi and a predation or flushing system which prevents excessive build-up of the primary organisms to block the filter. A filter presents opportunity for spatial variation in population vertically. There is also opportunity in a heavily slimed filter for aerobic populations at air-waste interfaces with anaerobic and sulfur reducing organisms below the surface layers of growth.

As a key to items relating to filter ecology, the following listing of references is presented:

Reviews and Summations: 8, 44, 231, 254, 461, 566, 730, 775, 779, 809, 987, 1228, 1251, 1253, 1471, 1817, 1821, 1825, 1826, 1828, 1912, 1916, 2031, 2237, 2238, 2266, 2364, 2367, 2714, 2731, 2732, 2734, 2800, 3126, 3168, 3432, 3575, 3576, 3699, 3712, 3714, 3715, 3759, 3868, 4076, 4083, 4266, 4384, 4403, 4429, 4473, 4579, 4641, 5456.

Growth Distribution: 173, 197, 523, 555, 777, 928, 987, 1612, 1820, 1821, 1825, 1826, 1829, 1914, 1916, 1917, 1919, 2442, 2628, 2713, 2715, 2742, 3144, 3721, 3824, 2903, 4384, 4396, 4404, 4405, 4414, 4429, 4648, 4672, 4677, 4821.

Algae: 209, 309, 343, 407, 653, 778, 779, 1158, 1213, 1735, 1757, 1821, 1826, 1987, 1994, 2088, 2246, 2266, 3336, 3467, 3480, 3715, 4404, 4405, 4473, 4717, 4923, 5173, 5577.

Bacteria: 43, 44, 88, 121, 185, 192, 230, 249, 254, 461, 567, 582, 617, 664, 718, 729, 730, 777, 779, 860, 927, 970, 1251, 1252, 1273, 1401, 1522, 1545, 1676, 1682, 1683, 1826, 1912, 1987, 2005, 2074, 2220, 2227, 2237, 2252, 2317, 2358, 2628, 2679, 3248, 3537, 3665, 3714, 3739, 3847, 3978, 3989, 4273, 4314, 4396, 4405, 4473, 4541, 4605, 4648, 4650, 4821, 4853, 5605, 5608.

Fungi: 88, 197, 235, 254, 309, 343, 449, 776, 778, 779, 1252, 1253, 1665, 1735, 1821, 1826, 1829, 1831, 1904, 1987, 2100, 2170, 2227, 2237, 2266, 2603, 3131, 3271, 3274, 3336, 3570, 3645, 3715, 3774, 3799, 4047, 4274, 4280, 4375, 4396, 4399, 4404, 4405, 4473, 4939.

Protozoa: 88, 174, 175, 176, 177, 461, 779, 812, 832, 850, 987, 1059, 1251, 1432, 1826, 1987, 2227, 2266, 2348, 2552, 2603, 2713, 2728, 3017, 3144, 3248, 3384, 3401, 3716, 3732, 3739, 4047, 4050, 4404, 4544, 4579, 4677, 4821, 4829.

Insects, Worms and Miscellaneous Life Forms: 146, 252, 373, 461, 578, 579, 620, 774, 779, 926, 987, 1228, 1365, 1475, 1480, 1492, 1723, 1815, 1816, 1817, 1819, 1821, 1823, 1824, 1825, 1829, 1869, 1914, 2101, 2145, 2221, 2506, 2730, 2731, 2732, 2733, 2734, 2735, 2738, 2740, 2754, 2755, 2894, 3131, 3143, 3170, 3258, 3338, 3425, 3507, 3567, 3568, 3570, 3931, 4101, 4185, 4343, 4410, 4411, 4415, 4677, 4737, 5390.

Pure Culture: 88, 332, 450, 567, 582, 1216, 1251, 1273, 1522, 1683, 1826, 3074, 2262, 2611, 2840, 3158, 3764, 4083, 4399, 4428, 4605, 4606, 4852, 5124, 5166, 5456, 5605, 5608.

SECTION XVII

PATENTS

An awareness of the significance of patenting various processes and modifications thereof dealing with biological trickling filters was indicated (877, 4181) by discussions of the significance of the developed technology. Throughout this review, brief mention has been made of typical patents issued on material pertinent to the section under consideration. It is beyond the scope of this review to consider an in-depth patent search, but patents may be regarded as an end-product of research. Therefore, it was deemed a section prepared as follows would be an efficient method of acquainting the novice with past issued patents and provide the contemporary practitioner with a reference source. By referring to the bibliography, one may observe those references which were noted to be specifically oriented towards patented information. No comments or critiques were considered necessary due to the specific nature of patent information which would require the interested reader to delve into the patent more deeply than may be done here.

For the purposes of organization and rapid review, the following categories have been included.

Patents for the general sewage treatment by trickling filtration are listed as follows:

338, 395, 542, 917, 1004, 1156, 1165, 1509, 1672, 1675, 1772, 1966, 1968, 2009, 2173, 2376, 2424, 2618, 2720, 3268, 3452, 3481, 3561, 3680, 4003, 4021, 4455, 4456, 4602, 4819, 4867, 4868.

Items of interest for the pretreatment of sewage for biological trickling filtration are found in the following issued patents:

1677, 2164, 2354, 3366, 3678, 3679.

There were several patents issued on various procedures for distributing the waste over the trickling filter such as follows:

386, 387, 396, 496, 524, 780, 1171, 1446, 1484, 1759, 1760, 1761, 1763, 1764, 1765, 1767, 1967, 2339, 2349, 2529, 2530, 2637, 2854, 3490, 3597, 3685, 3898, 4340, 4836.

The media used for biological trickling filters have been covered in considerable detail under construction materials, and patents were issued, typically, as follows:

Preceding page blank

90, 312, 463, 917, 940, 965, 1052, 1364, 1482, 1661, 1705, 1976, 2215, 2216, 2230, 2350, 2588, 2706, 2836, 2865, 2866, 2986, 3107, 3438, 3495, 3895, 4265, 4361, 4362, 4454, 4603, 4763.

Problems arising from odor were very closely related to ventilation and underdrains which gave rise to several patents being issued, typically, as follows:

12, 169, 170, 369, 370, 489, 914, 1212, 1472, 1595, 1597, 1598, 1599, 2172, 2325, 2588, 2694, 2810, 3476, 3523, 3822, 4002, 4097, 5637.

Treatment was not considered complete in most cases without some form of post-treatment on biological trickling filters which involved various forms of clarifiers and sludge disposal techniques. In this category, the following patents were issued:

1002, 1428, 1435, 2720, 3677, 3679, 3897, 4367.

Several investigators were unsatisfied with the performance of biological trickling filters and suggested process modifications using trickling filters as the basis in combination with other unit operations or changes in the standard design of trickling filters. The issued patents are given in the following list:

141, 368, 544, 680, 757, 781, 782, 866, 966, 1001, 1003, 1164, 1307, 1435, 1470, 1481, 1485, 1600, 1622, 1841, 1854, 2155, 2267, 2514, 2633, 2707, 2944, 2954, 2982, 3169, 3469, 3495, 3890, 3965, 4096, 4211, 4310, 4581.

Cleaning and maintenance of biological trickling filters and their appurtenances required techniques of sufficient uniqueness that patents have been issued, typically, as follows:

398, 2632, 2694, 2706, 2864, 3155, 4098.

The above references were offered in this manner in the text of the review because of the strong relation between research and development and patents. It is suggested that with these references and those provided in the discussion sections the reader should be able to know the patents in the field. Due to the activity of investigators applying for patents, it is to be noted that this partial list has been gathered only as a basis and is by no means considered comprehensive.

PART IV

APPLICATION OF TRICKLING FILTERS TO SPECIFIC INDUSTRIAL WASTES

This section includes significant information on the performance of biological trickling filters on several specific industrial wastes which appeared frequently in the literature. The categorization of the wastes was established by similarity of characteristics, trends noted in texts, and groupings in the literature. Within each section, after a discussion of the characteristics and occurrence of the waste, there are the following subcategories:

1. Pretreatment required.
2. Efficiency of trickling filter application.
3. Comparison to other methods of treatment.
4. Post-treatment and effluent quality.
5. Special operational problems.

Each waste is separately critiqued, noting information on past, present and future applications of the process. The category of institutional and military waste was included in this section because of its unique characteristics. A few of the subcategories were condensed due to the redundancy of reports, such as use of humus tanks. However, post-treatment is reported with every application.

SECTION XVIII

BREWERY AND DISTILLERY WASTES

Trickling filters have been used extensively for over fifty years as a satisfactory method for treating brewery wastes. In 1916, Emmerling (1170) recommended trickling filters because the management is simple and requires little attention after the process is operational. A survey by Faber (1223) of brewery wastes in Chicago showed BOD in the 1200 mg/l range, suspended solids levels at 600 mg/l, and nitrogen averaging 50 mg/l. Efforts to coagulate this waste chemically were unsuccessful because of the high degree of soluble BOD in relation to the concentration of suspended solids.

In most cases, brewery waste was blended with domestic sewage prior to treatment. A typical treatment plant included grit removal, primary clarification, two trickling filters in series with sedimentation between each filter, and final clarification. Variations in treatment consisted of pre- and post-chlorination, and substitution of an activated-sludge unit for the second filter. Due to the easily oxidative nature of the waste (4782), retention times in settling tanks were held up to 1.5 hours (5105). Hydraulic loading rates for domestic waste - brewery waste blends were reported to run from 75 gal./yd^3/day (1,350 gal./ft^2/day), (Tidswell, 4389 4390) to 100 gal./yd^3/day (1,800 gal./ft^2/day), (Moncur, 5265). Recently, Chipperfield (681) described three years' experience of brewery waste treatment on both single and multistage trickling filters constructed of plastic media.

The main waste byproduct from distilling operations was reported as thin stillage. This material is acidic (pH 3.5 to 4.5), had a BOD$_5$ of 25,000 to 45,000 mg/l and contained 3 to 5% solids (414, 4071). Boruff and Blaine (415) claimed that 85% of the stillage solids in the U.S.A. were recovered as animal feed. Analysis of waste water discharged from an Indiana distillery (3642) demonstrated that more than one-half of the BOD resulted from process wastes. About 77% of this waste was due to the condensate from the quadruple-effect evaporators used to concentrate the stillage. This condensate had a pH of 3.8, a BOD of 685 mg/l, less than 1 mg/l of nitrogen, no phosphorus, and 1 to 1.5 mg/l of copper from copper tubes and piping of the evaporators. Biological filtration was a satisfactory method of treating the resulting waste from stillage (415). Single stage filtration had been employed, and Laurent (2635) documented satisfactory performance utilizing double filtration. Stillage produced from the distillation of wood waste contains unfermented sugars, furfural, and organic acids and has a BOD of 6,000 mg/l according to Bollen (392).

Preceding page blank

PRETREATMENT REQUIRED

Various investigators have studied pretreatment schemes in an effort to facilitate the treatment of brewery wastes across trickling filters. Wisely (4782) related that the wastes at the sewage plant in Highland, Illinois, were aerated in a large hydraulic dosing chamber to keep them fresh and alkaline. Similarly, according to Rowe (3701), lime was added to the wastes to maintain alkalinity, but large quantities of sludge were produced. Raux and Maringe (3511) and Moreau and Aubertin (3089) reported on ferric sulfate and lime being used for an identical purpose in France, while the sewage works in East Ham, London, (5214) used lime and chlorinated copperas. Oliver and Walker (3239) tried to avoid adding lime and instead applied the waste to filters with limestone media, but this proved unsatisfactory because erosion occurred and the stone tended to knit together, thus reducing the available surface area.

Chlorine has been added to the primary filter influent for the control of filter flies (3179). Faber (1223) found that the intermittent addition of 40 mg/l chlorine was adequate to accomplish this control.

Trickling filters have also served as a useful pretreatment device for other forms of treatment on brewery wastes, particularly the activated-sludge process (2035, 4583). At Chilton, Wisconsin, (4890) blended waste was screened, settled, passed through high-rate filters, settled, aerated for 4 to 6 hours, and again settled. Sudden changes in the waste water caused by the brewery wastes were balanced by passage through the filters, and the operation of the activated-sludge plant was not affected.

Waste waters from distilleries have a high content of organic matter and are difficult to treat by an aerobic process of sewage treatment owing to the high oxygen demand of the liquors. Bloodgood (361) obtained satisfactory results by anaerobic digestion of the waste, followed by treatment on trickling filters. Roberts and Hardwick (3642) found it necessary to add supplementary nitrogen and phosphorus to the evaporator condensate prior to the application on the filters. Maiz (2841) and Cosculluela (792, 339) found that it was necessary to dilute distillery slops with three to four times their volume of water, followed by sedimentation and inoculation with ammonifying bacteria. The resulting fermentation eliminated the putrescible fraction of the effluent and was amenable to biological filtration where the ammonia would be oxidized to nitrite and nitrate in two-stage percolating filter treatment. Buswell (564) used a similar scheme except that the slop was fed to two digester tanks in series and the digested effluent was diluted with final effluent before being passed to a single trickling filter. Under some conditions lime was added to the acidic waste before filtration (3693).

Distillery wastes from the manufacture of wine and brandy pose slightly different pretreatment problems. Research by Hodgson and Johnston (1969) indicated the addition of lime and sedimentation. Sulfuric acid was added to adjust the pH back to between 7 and 8 before the waste was two-stage filtered. This effluent was then sent to a domestic waste treatment plant. Soeiro and Lima (4099) recommended mixing wine and brandy waste with cooling water, adding lime, and then settling. Hydrochloric acid neutralized the effluent prior to processing by trickling filters equipped with recirculation of effluent. At Sonoma, California, Vaughn et al. (4517) noted that the brandy stillage was treated to remove tartrate, the pH was adjusted upward, and then the waste was diluted with condenser water and waste wash water prior to sewer discharge. Tartrate removal was accomplished by the "hot throw" method using calcium hydroxide and calcium chloride.

In the treatment of wood distillation wastes, experimentation by Riley et al. (3616) proved that mild autooxidation was a necessary preliminary treatment to reduce the toxicity before biological filtration could function. Coagulation with lime removed suspended solids satisfactorily.

EFFICIENCY OF TRICKLING FILTER APPLICATION

Good removal rates of soluble BOD, suspended solids, and dissolved nutrients contributed by brewery wastes have been attainable with trickling filters (1963, 4325). Wisely (4782) found that the hydraulic fluctuations caused by the irregular dosing of the filter from a large dosing tank affected the final efficiency. Investigations by Bushee (551) proved that a brewery waste containing 370 mg/l BOD_5 and 340 mg/l of suspended solids gave better results when treated with two filters operated in series than when run in parallel. Measurements of BOD showed that more of the impurity was removed in the first stage than in the second. Krum (2575) stated that complete treatment of a combined domestic brewery waste in Allentown reduced organic nitrogen from 17.05 to 3.66 mg/l, ammonia nitrogen from 12.23 to 1.05 mg/l, oxygen demand from 129 to 31 mg/l, suspended solids from 186 to 35 mg/l, and BOD from 213 to 29 mg/l. A Houston brewery (5105) was able to achieve 90% BOD and 75% suspended solids reduction through a two-stage trickling filter process. Serving as pretreatment devices or roughing filters prior to activated-sludge units, trickling filters assisted in attaining total treatment efficiencies of 95 to 99% of the BOD and of 75 to 90% of the suspended solids (2522, 4890).

The efficiency of trickling filters for the treatment of distillery wastes was quite good. Without preceding anaerobic digestion, biological filtration was capable of achieving a 77% reduction in BOD according to Roberts and Hardwick (3642).

Initial removals were only in the range of 33%, however, until the filter microorganisms became acclimatized to the copper present from the evaporators and 30 mgad (690 gal./ft^2/day) were loaded at 2 lb BOD/yd^3/day (74 lb BOD/1,000 ft^3/day) after some pretreatment. Davidson (878, 879) reported on a Maryland distillery which produced a waste having a BOD of 700 mg/l. Recovery of cattle feed after distillation and passing the remaining waste material through high-rate trickling filtration made BOD removals of 99.9% possible. Sawyer and Anderson (3839) ran 1% rum waste through a two-stage trickling filter plant equipped for a recirculation ratio of three volumes of effluent to one volume of sewage. When the primary filter was loaded at a rate of 2,590 lb of BOD/ac-f/day (58.6 lb of BOD/1,000 ft^3/day), the average BOD was reduced from 485 to 19.7 mg/l. The overall BOD reduction of a wine and brandy stillage-sewage mixture, as reported by Vaughn (4517), averaged at 88% for a three-year period.

Plastic media have also been investigated for processing distillery waste. Askew (98) treated waste from a distillery containing 922 mg/l BOD on two-stage plastic media packed towers with the average BOD loads and removals at stages one and two being 3.5 and 1.1 lb/yd^3/day (129 and 39.6 lb of BOD/1000 ft^3/day) and 68.6 and 78.4%, respectively. Treatment of wood distillation waste on trickling filters at a rate of 1 gal./ft^3/day with aeration and recirculation appeared to be the most desirable process with 50% BOD removal (392).

COMPARISON TO OTHER METHODS OF TREATMENT

Several investigators (4390, 5214) have compared the relative effectiveness of trickling filters for brewery waste treatment with other methods. Both trickling filters and activated sludge have been used alone or together to process brewery waste or combined brewery-domestic waste. Allen (51) reported that Regina, Saskatchewan, Canada, used both processes, with 60% of the flow treated by trickling filters and the remainder treated by the activated-sludge process. Bushee (551) asserted that undiluted brewery wastes were adequately processed by series filter operation, whereas the contact aeration process yielded unsatisfactory BOD reductions. Advantages of biological filtration over the activated-sludge process, according to Jackson (2251), included more economical operation, less sensitivity to shock loading, and reduction of the cost of treatment by the recovery and sale of animal feed. However, Newton et al. (3180) described the conversion of an existing trickling filter plant at Frankenmuth, Michigan, to the activated-sludge process to achieve a higher degree of treatment efficiency. The recent advent of plastic media for biological filter packing has stimulated evaluation studies by Askew (98) and Chipperfield (681). Advantages cited are savings in capital costs over conventional filters in activated-sludge plants in the order of magnitude of 25 to 55%.

Trickling filters were generally accepted in the treatment of distillery waste when compared to other processes. Davidson (879) pointed out that the activated-sludge process was not acceptable for treatment of these waste waters since they contain some copper from the copper distillation equipment and this copper accumulated in the sludge and had a toxic effect on the microorganisms. According to Boruff (414), treatment by the activated-sludge process was not successful unless the wastes are first digested, then mixed with sewage. Smith and Fargey (4071), however, reported that the total solids and the chemical oxygen demand could be reduced by both activated sludge and biological filtration, and still greater reductions were achieved operating the two processes in series, e.g., COD reduced by 95%. Sawyer and Anderson (3839) studied rum distillery wastes and discussed the difficulties in treating such wastes by standard trickling filters or by the activated-sludge process. One source (4925) stated that, although an activated-sludge unit is being installed at a new distillery, biological filtration was the predominant form of treatment. Advantages of plastic (PVC) media for handling distillery wastes in comparison to conventional filter media were also described (4965).

POST-TREATMENT AND EFFLUENT QUALITY

Trickling filters are rarely used as a post-treatment type facility. Of the plants utilizing this concept, Artist (96) was able to verify that the trickling filters at Wakefield, England, which were preceded by the activated-sludge process, did function well and with no filter flies. It was speculated that most of the food normally available to these flies was removed in the aeration tank.

Normally, ordinary sedimentation followed the trickling filter operation in a system designed for handling distillery wastes. Stevens (4211) described the separation of liquid from distillery slop by either settling or centrifugation and the treatment of the liquid on a trickling filter before being mixed with a reagent, such as calcium carbonate, to precipitate an insoluble lactate which was filtered off. Part of this filtrate or the original trickling filter filtrate, or a mixture of both, may be concentrated and re-fermented. Another form of post-treatment was reported by Schieck (3863). He used a circular aeration tank for further treatment of a tar distillery waste water after biological filtration.

SPECIAL OPERATIONAL PROBLEMS

Past experience demonstrated that brewery wastes when mixed with sewage were satisfactorily treated with two-stage series biological filtration (551, 2575, 5105). Moncur (5265) discussed the pilot plant operation of six filters in four ways:

single filtration, single filtration with recirculation of effluent, series (double) filtration, and alternating double filtration. Tidswell (4389) followed up this research with his own and came to the conclusion that double filtration should be practiced in preference to alternating double filtration. It was interesting to note, however, that seven years later he reversed his position after obtaining operating data from the full-size treatment plant (4391). He also recommended that the order of the filters be reversed every two weeks (4390). Within the past ten years, most trickling filter plants were designed to function either as single, double, or alternating double filtration units (4582, 5274, 5560). One source (5228) did mention that alternating double filtration was used more frequently if the proportion of brewery waste to sewage increased significantly. Severe corrosion in a sewerage system resulting from the presence of brewery waste rich in organic sulfur compounds, which evolved as hydrogen sulfide from bacterial action, prompted the use of plastic material for the construction of pipes, channels, and sprinkler equipment at a new biological filter plant (2264).

The treatment of distillery waste has not been without problems (5390). Blohm (357) recorded the difficulty encountered in a Maryland plant when distillery waste water amounting to 1% of the total domestic sewage flow was introduced into a conventional single-stage trickling filter plant. Excessive septicity occurred in a primary settling tank which was caused by foaming in the digestion tank and overflowing, followed by frothing over of solids onto the trickling filter. Normal operation was not resumed until the trade waste was diverted from the treatment plant. Due to the high oxygen demand of these wastes, Sawyer and Anderson (3839) have advocated the installation of a separate piping system to transport rum distillery waste directly to a municipal plant. The mixing of this particular waste with sewage created objectionable anaerobic conditions in the sewer system.

Critique

Brewery and distillery wastes can be adjusted to be treated adequately by trickling filters. Advantages of using trickling filters, and specifically filters with plastic media, were adequately reported. It appears that the technology for treating this waste is well developed. Now, developments for automatic control, recoverable byproduct, and other aspects are being studied.

The high oxygen demand of these wastes caused concern to some investigators because low-rate filters developed nuisance conditions. A satisfactory approach was high- or super-rate filtration in series or in series with other systems. Anaerobic treatment ahead of trickling filters found some application, but the attendant nuisance odors must be considered in the design. The reports reviewed indicated the necessary pretreatment and post-treatment required to make these wastes biodegradable. Acclimatization was required, and some problems with toxic metal contents were to be expected, but the wastes were generally treatable by biological filtration to conform with the required standards.

SECTION XIX

ORGANIC AND INORGANIC CHEMICAL WASTES

Chemical wastes as used here are defined as the effluents from installations in the chemical industry, and it is not meant to cover the chemical characteristics of all wastes. It was estimated in 1966 by Sadow (3809) that $40 million annually were spent in operating costs and 1700 full-time personnel were employed by the chemical industry to fight pollution. The types of wastes, their concentration and volume vary widely from plant to plant. A large number of the chemical plants separated their wastes, allowing uncontaminated storm and cooling water to be discharged directly to the river, while process waste waters were treated by various methods. The waste waters from petroleum production were often odoriferous, highly colored, and had high organic content (BOD). Waste waters from the production of dimethyl terephthalate, in Russia, were turbid, odorous, and intense yellow-orange, contained considerable amounts of aliphatic acids, and had a high BOD (4001).

Pettet suggested (3355) that,by modifying manufacturing processes, it was possible to reduce the volume and strength of the waste water, and savings in raw materials and water were realized. He recommended that waste waters containing organic substances be treated separately from those containing organic substances. In general, the inorganic wastes are treated by chemical methods, and the recovery of these materials may be of importance in the manufacturing processes, while the organic wastes may be biologically treated. Many chemical plants are so large and the waste so complex that it is virtually impossible to separate the organic and inorganic wastes. Harlow and Powers (1743) reported in 1947 that wastes from the production of 400 chemicals in 500 buildings totaled 200 mgd which required disposal. About 125 mgd of clear, warm condenser waters was discharged directly to the river, but phenolic wastes, varying from weak (1.5 ppm) to strong (700 ppm), were separated and treated by separate means.

Experiments were carried out by Brink and Thayer (462) on the treatment of cyanide waste waters by biological filtration. Preliminary results indicated that concentrations of free cyanide as high as 150 ppm were removed and complex cyanides containing metals such as copper were the most difficult to treat. Liquid organic wastes containing formaldehyde and methanol were successfully treated when combined with domestic sewage and cooling water (5047). The treated water was not toxic to fish when discharged to the river.

The manufacture of synthetic fibers produced new waste treatment problems. Sadow (3808) described the treatment of wastes containing acrylonitrile and zinc from the manufacture of

Preceding page blank

acrylic fiber. Dryden et al. (1039) treated the wastes from a pharmaceutical plant manufacturing antibiotics, synthetic vitamins, and cortisone by biological filtration. The treatment of effluents from pesticide manufacturing was described by Sharp and Lambden (3971). This plant manufactured dinitro-orthocresol insecticides, copper oxychloride fungicides, DDT insecticides, and a number of other weed killers and insecticides incorporating oils, solvents, and surface active agents. These wastes, typical of many chemical plant effluents, were strongly bactericidal and were not amenable to biological treatment in their raw state.

PRETREATMENT REQUIRED

Treatment of organic waste waters (4545), such as from the manufacture of pharmaceutical-type products and organic chemicals, by biological filtration was feasible, but preliminary treatment and pilot plant studies were often necessary. Many chemical wastes required neutralization and equalization. This procedure was often combined with primary sedimentation, as reported by Sadow (3808) for the treatment of a synthetic fiber waste. The zinc from the fiber waste was precipitated by coagulation with caustic soda and ferrous sulfate in an upward flow tank, and the effluent mixed with sanitary sewage before it was pumped to plastic media trickling filters. Dickerson discussed (951) the need for neutralization and settling before biological treatment of the waste liquors from the manufacture of a smokeless powder, which contained decomposition products of nitrocellulose, alcohol, acetone, ether, nitric oxides, nitric and sulfuric acids, waste from dehydration, and some soluble organic materials. Powers (3451) and Harlow and Powers (1743) stated that lagoons were used for storage and blending of strong phenol wastes. Lagoons or ponds were also used for cooling.

Loewnstein observed (2751) that an alcohol still residue and spent gas liquor from a South African coal gasifier had a temperature of 140°F and contained up to 30 ppm of phenol. This waste was passed through spray ponds to reduce the temperature to 95°F before biological filtration. More recently, Loewnstein and Waal (2752) reported that the same waste now receives additional pretreatment by chemical coagulation using ferrous sulfate and hydrated lime prior to biological filtration. Since the wastes from pesticide manufacture are highly toxic, Sharp and Lambden (3971) described the preliminary treatment as adsorption on activated charcoal, followed by addition of hydrated lime, settling, and neutralization with sulfuric acid. They further stated that wastes of this type were mixed with settled sewage or a commercial biological inoculum before treatment on percolating filters.

EFFICIENCY OF TRICKLING FILTER APPLICATION

One of the more common wastes from the chemical industry is phenol. Powers (3451) and Harlow and Powers (1743) discussed the application of trickling filters to remove phenol dosed at a rate of 10.2 mgad (235 gal./ft^2/day). The concentration of the phenol applied to the filters was normally 30 to 50 ppm and 4.29 to 9.0 pounds of phenol was removed per day/ 1,000 ft^3 of filter media when the temperatures of the waste water were 56° and 83°F, respectively. At the same temperatures the reduction in BOD was 15.8 and 27 lb/1,000 ft^3/day, respectively.

Sadow (3809) reported that phenol removals of 99.9% and COD reduction of 80 to 85% were obtainable by roughing filters and aeration devices. The wastes from a synthetic resin plant were applied to trickling filters at the rate of 0.5 lb BOD/ yd^3/day (18.5 lb BOD/1,000 ft^3/day), which allowed a margin for the possible inhibiting effect of toxic substances (947). Diammonium phosphate had previously been added to the waste water to provide nutrients for the filter organisms and the reduction in BOD varied between 79 and 95%. The content of phenols in the crude waste waters reached 50 ppm and the efficiency of their removal varied from 90 to 99%.

The River Spree near Berlin, Germany, was protected from the discharge of phenol from a tar distillery and chemical factory by a two-stage biological treatment plant (4547). The plant was equipped with a tower percolating filter and an activated-sludge unit. The overall reduction in the concentration of phenol was 95%, and the BOD_5 was reduced by 67%. The percolating filter removed 10% of the phenol and 32% of the BOD. Mills (5354) discussed the operation of a pilot plant utilizing a plastic media percolating filter and an activated-sludge tank to treat phenolic and 2,4-D wastes. Effluent from the activated-sludge tank was recirculated to the percolating filter and sludge was passed to a sedimentation tank and then returned to the system. Although 99 to 100% of the phenol was removed, the 2,4-D waste waters (main constituent dichlorophenol) was more difficult to treat and 5:1 dilution was necessary.

In 1959, Erlebach et al. (1188) showed that removal of fatty acids from waste waters by slag filters was analogous to the removal of phenols. The retention of fatty acids exceeded the adsorption capacity of the slag, although the efficiency of the filters did not decrease. Dickerson (948) reported that an exceptional high-rate trickling filter was dosed at 50 mgad (1,150 gal./ft^2/day) with a recycle ratio of 40:1 with an influent containing phenol, formaldehyde, and resin oil waste.

A plastic media percolating filter was used by Harlow et al. (1740) and Shannon (3968) to remove 90% of the BOD, 60% of the COD, and 95% of the phenol from a petrochemical waste. For loadings of formaldehyde up to 260 mg/l, Dickerson (948) removed 2.59 lb of formaldehyde per cubic yard of stone (96 lb/1,000 ft^3/day), and the overall efficiency of removal by the filter was 23 to 40%. He recommended (948, 949) that the pH be controlled between the 4.5 and 8.5 range. Organic wastes containing formaldehyde (573) were passed through percolating filters after mixing with process water and domestic sewage.

Paleni described (3276) the treatment of waste waters from a vegetable oil refinery and chemical plant which had a BOD of 5,000 to 19,000 and an average pH value of 1.5. The Ingram controlled biological filtration process in packed towers was used for these waste waters to produce an effluent BOD of 50 and a pH value of 7.0. Strong waste liquors (3,000 to 100,000 mg/l BOD) from the manufacture of antibiotics, vitamins, and sulfa drugs were evaporated and incinerated. However, Reimers et al. (3551) reported that these wastes could be combined with weaker wastes and adequately treated by high-rate trickling filters. In the pilot plant, four- and six-foot deep filters were used, with clarification necessary only for the final effluent. BOD_5 removal (80%) was obtained in a single-stage operation, and designed organic loadings of full-scale units were reported as 1.9 to 2.0 lb/yd^3/day (70 to 74 lb/1,000 ft^3/day).

The waste waters from rosin extracting processes containing resinic and fatty acids, polymerized terpene hydrocarbons, and other organic substances had a BOD_5 up to 13,000 mg/l (3663). These wastes were diluted with river water or domestic sewage to give a BOD of about 400 mg/l influent for treatment. In a typical experiment with the percolating filter, the BOD was reduced to 46.8 mg/l.

To remove the color and BOD from wastes from the production of pigmented lacquer materials, three slag filters in series were used by Grünwald et al. (1613). When the concentration of organic matter in the influent changed, there was a direct corresponding change in efficiency of the filters and in the amount of organic matter retained. The slag filters lowered the pH value of alkaline waste waters and raised the pH value of acid waste waters, with the overall efficiency of the three filters averaging ~32.7%. The waste waters from the manufacture of synthetic rubber in Romania were reported by Munteanu et al. (3126) to be treated in high-rate aerated percolating filters after pretreatment. The filters operated with hydraulic loads of about 0.5 to 1.0 m^3/m^2/hour (295 to 590 gal./ft^2/day) and five-day BOD loads of about 0.3 to 0.5 kg/m^3/day (18.7 to 31 lb/1,000 ft^3/day). The addition of domestic sewage was unnecessary, provided that phosphorus was supplied in doses of 3 to 5 mg/l.

Blarigan and Lamb (352) reported the results of a statistical interpretation of pilot plant studies which involved single- and two-stage trickling filters. They found that temperature had a marked effect on BOD removals at all loadings and recirculation ratios, and the effect was more pronounced at higher recirculation ratios. The effect of BOD loading was small in comparison to the effects of temperature and recirculation. However, the effect of recirculation was more pronounced with single filtration than with two-stage filtration.

COMPARISON TO OTHER METHODS OF TREATMENT

Trickling filters have often been compared with activated-sludge units, although the two processes may be combined. Shannon described (3968) an installation which treated mixed liquor from the activated-sludge unit. The filter gave considerable oxidation and made it unnecessary to waste excess sludge. However, in periods of shock loadings or excess demand on the treatment plant, the filter was operated in parallel with a second filter which preceded the activated-sludge unit.

During experiments on TNT wastes, Schott et al. (3885) found that difficulties in operation would occur in activated-sludge plants where 5% or more TNT was in the waste waters. However, a trickling filter, when dosed at the rate of 1 mgad (23 gal./ft^2/day) was capable of treating sewage containing 10% TNT waste waters without appreciable decrease in the percent reduction of BOD. When dosed at the same rate with sewage containing 25% TNT waste waters, the percentage reduction of BOD was reported to be considerably decreased. Phenol-containing wastes were treated (4547) by combined trickling filter and activated-sludge process and 85% of the phenol and 35% BOD were removed by the latter unit.

Reimers (3551) reported that strong waste liquors (3,000 to 100,000 mg/l BOD) from the manufacture of antibiotics, vitamins, and sulfa drugs were successfully treated by high-rate trickling filters. Previously, the wastes had been treated by other methods such as evaporation and incineration, but the biological treatment improved the effluent emptying into the river, and was more economical.

POST-TREATMENT AND EFFLUENT QUALITY

Trickling filters as roughing filters, followed by activated sludge, are frequently used for treatment of chemical wastes, and have been covered extensively in a previous section of this survey. Several authors (952, 956, 1743, 3451, 3809, 4547) have discussed the use of this approach of dual treatment. A petrochemical plant in Texas (4971) reused the effluent from the dual system after sedimentation for cooling purposes.

Dickerson (948) noted that lagoons could be used if further purification after the trickling filter was required. Liontas (2723) pointed out that a pharmaceutical plant manufacturing antibiotics and synthetic chemicals used intermittent sand filtration after two-stage biological oxidation in high-rate percolating filters and secondary sedimentation. Chlorination was used following the sand filtration, and 98% average overall reduction in BOD was noted.

SPECIAL OPERATIONAL PROBLEMS

The effect of pH on biological systems was well documented, as confirmed by Walter (4592) during pilot plant studies on the combined treatment of sewage and textile waste waters. A roughing percolating filter removed about 60% of the applied BOD with loadings of 3,000 to 6,000 lb/ac-f/day (69 to 138 lb BOD/1,000 ft^3/day). The greatest removals occurred with influent pH values of 8 to 9 and the reduction in BOD decreased as the pH value increased to 11 or 12. Biological filtration reduced the pH value of the waste when the initial value was 8 to 11, but above and below this range the filter had little effect on the pH value of the waste. Little additional reduction in BOD was achieved by settling the primary filter effluent and, since a second stage of biological treatment was necessary for this waste, it was concluded that intermediate sedimentation was not justified.

Bucksteeg (522) observed that cyanide waste was only reduced about 30% in percolating filters and this was due mainly to aeration. When the filter medium was replaced with low temperature coke and the concentration of cyanide was increased from 100 to 200 mg/l, it was found that the effluent contained only about 0.1 mg/l cyanide. Further experiments indicated that the cyanide adsorbed on the coke was destroyed within a few days, which left the adsorption surfaces free to adsorb more cyanide. He suggested that a process similar to this with a two-layer percolating filter be used to treat municipal sewage containing cyanide waste waters. The two-layer percolating filter is composed of a top layer filled with coke and ceramic material to destroy the cyanide and a bottom layer filled with a conventional medium for biological oxidation.

Dickerson (951) noted that, when the hydraulic rate of a trickling filter was increased from 16 mgad to 39 mgad (368 to 897 gal./ft^2/day), *Psychoda* flies were no longer a nuisance. Loadings at 8 mgad (184 gal./ft^2/day) minimized ponding problems (951). An ecological study was made by Reynoldson (3575) of a sewage containing a high proportion of chemical waste. He found that *L. lineatus* was scarce and *E. aldidus* was more abundant, but the total worm population was numerically much less than found in percolating filters of other works. The worms were fewest at the surface and the population was relatively high in the area surrounding the cental distributor, which could explain ponding problems.

Hess (1903) discussed the problem of acid waste waters and oil in waste waters at a treatment plant employing percolating filters. The waste was comprised of effluent from food canning, processing of milk, manufacturing of cheese, plating and pickling of metals, manufacture of dry batteries and coolants, and oil-bearing degreasing wastes. The effects of oil were overcome by treating the filters with emulsified ortho-dichlorobenzene and breaking up the surface of the medium.

Ingols (2219) discussed the difficulties in sewage treatment at a municipal plant caused by the presence of synthetic detergents in the sewage. He found that the presence of detergents interfered with sedimentation and resulted in overloading of the percolating filters. A pilot plant study was made by Wilson (4756) for a chemical plant in North Wales, and the breakdown of pure chemicals in experimental percolating filters was examined. Although acetic acid depressed the rate of breakdown of phenols in the filters operating on mixed chemical waste waters, the acetic acid was fairly readily destroyed. A study of Jenkins (2281) on the biological oxidation of stearic acid in percolating filters showed that sodium stearate was oxidized if nitrogen, phosphorus, and potassium were present. The oxidation occurred more readily in the presence of domestic sewage, but at certain concentrations of stearate the filters might become choked. However, these concentrations were greater than that likely to be found in most waste streams. Munteanu et al. (3126) noted that copper accumulated in the biological film and caused difficulties in subsequent sludge digestion during the treatment of waste waters. In the treatment of effluent from pesticide manufacturing, Sharp (3971) estimated the cost at £1.00/1,000 gallons ($2.50/1,000 gal.) including labor, where the treatment consisted of passing through charcoal towers, treatment with hydrated lime, settling, neutralization with sulfuric acid, and treatment on percolating filters before final sedimentation.

Sadow (3809) reported that the chemical waste treatment plant at Texas City, Texas, had an annual operating budget of $750,000 per year including all fixed charges, taxes, insurance, and depreciation. Roughing filters and aeration devices were used for biological treatment, with 99.9% of the phenol and 80 to 85% of the COD being removed.

Critique

Papers on the treatment of chemical wastes with biological trickling filters were published frequently, and the investigators demonstrated knowledge of physical, chemical and biological treatment techniques. The inorganic wastes were usually treated chemically. However, only occasionally reported, but of rather common knowledge, was the heavy reliance on dilution to handle inorganic chemical wastes and thermal pollution.

Biological trickling filters have been of value for high organic strength waste of varying character and flow. The examples of chemical wastes reviewed using biological trickling filters were a small part of the total literature. The pretreatment required was frequently in the form of equalization and suspended solids removal. Post-treatment was usually clarification, additional oxidation and disinfection. The toxicity of some chemical waste required deep-well disposal of the treated effluent.

The chemical industry, as well as others, has apparently spent much effort in time and money to render their waste waters less objectionable to the environment. Unfortunately, systems such as the biological trickling filter, even operating at high efficiency, are very expensive and one must reflect if there is a better way and if the technology for treatment of these wastes is really developed. If a plant removes 90% of the BOD of an influent which has 500,000 mg/l BOD, an effluent of 50,000 mg/l BOD would still be discharged to the receiving waters. If one were to consider the total pounds of BOD discharged per day to the receiving body rather than concentrations, the performance of the sewage plants becomes more alarming. The recent literature reflects these concepts and engineers and scientists are cognizant of these weaknesses and are endeavoring to rectify them.

SECTION XX

GAS AND COKE PLANT WASTES

The processes described herein and their associated wastes deal with the production of coke by carbonization of coal and the conversion of solid or liquid fuels to gaseous products that are suitable either as a source of energy or as a feed material for chemical synthesis. In the United States, natural gas has largely supplanted manufactured gas as a fuel source. In other countries, however, manufactured gas is still the principal source of gaseous fuels. The manufactured gas industry can be subdivided into two distinct and different industries: the production of fuel gases, and the production of feedstocks for chemical synthesis. The gas industry is closely related to the coke industry, since coke is also a major raw material for gas production.

Fuel gas is produced by heating soft coal or oil with air and steam, oxygen and steam, or hydrogen. The principal products of this gasification are CO, H_2 and CO_2 in decomposed steam; there are also small to moderate amounts of CH_4, N_2, and traces of sulfur-bearing gases. These gases subsequently are used directly for fuel purposes or as feedstocks for the production of ammonia, methanol, or a variety of liquid fuels.

The production of coke, which is closely related, consists of the carbonization of coal upon heating in the absence of air at an elevated temperature, and driving off volatile products.

In all of these processes, the primary waste products result from gas scrubbing and solid quenching operations. Considerable quantities of ammonia, phenol, cresols, sulfides, cyanides, thiocyanates, various tars and other residues are discharged in liquid wastes from vapor condensates from gas manufacture and from coke quenching operations. These compounds have a high oxygen demand, are toxic, and impart taste and odors to the receiving waters. The removal of phenolic compounds from these wastes has been of prime concern because of their low detectable concentrations. Methods of treatment of these wastes have included biological oxidation, through the use of trickling filters or activated-sludge units, or various chemical methods, primarily oxidation, filtration, precipitation, and extraction.

Consideration of the biological and ecological conditions arising upon discharge of gas and coke plant waste into receiving waters was reflected in the literature. Meissner (2961) made special reference to the removal of phenol and ammonia from coal-associated wastes and gave account of the biological conditions of a number of rivers affected by such wastes. Bandt (161) discussed the origin and harmfulness and the treatment of phenolic waste waters. A summary of the literature dealing with the volumes, composition, and treatment of gas works liquor and effluents has been compiled (4992). Bondy and Priestley (400) reviewed legislation concerning river pollution with special reference to the waste waters from gas and coke works.

The general treatment of phenol-containing effluents was considered in two early papers. Prüss (3470) and Lesperance (2686) reviewed the biological treatment of phenolic waste waters and made special reference to the need for fundamental design criteria. Trickling filters were recommended for consideration where treatment was required for large volumes of warm waste waters containing low concentrations of phenol. Drabek (1024) investigated the use of slag filters for the treatment of phenolic waste waters. Solin (4105) purified generator effluents on slag filters after preliminary detarring. Zdybiewska and Bursztynowicz (4854) reduced the phenolic content of the waste water using acclimated organisms on blast furnace slag. Chipperfield (675) reviewed the basic requirements for plastic filter media treating these wastes. Noble (3194) presented graphical results on the treatment of spent gas liquor on plastic filters. Three waste treatment systems for waste containing phenolics from chemical manufacturers, including biological treatment, were described by Smith (4083).

PRETREATMENT REQUIRED

Pretreatment of coke and gas plant wastes was primarily dilution with domestic sewage or recirculated effluent. Zdybiewska (4852) preconditioned blast furnace slag with municipal sewage before introducing phenolic waste waters from coking plants for treatment. Mulls and Thompson (3123) diluted coke plant waste with domestic sewage followed by treatment at the municipal sewage works. Taubert (4308) stated that gas works waste waters were diluted with well water or by recirculation with about 80% of the filter effluent. Lesperance (2686) recommended dilution of phenolic waste waters to reduce the toxic effects upon microorganisms. Slater (4048) obtained satisfactory treatment of ammoniacal liquor from gas works upon diltuion with sewage, clarification on sand filters, and subsequent biological oxidation on trickling filters. Hurley (2105) diluted crude gas liquor seven times with volumes of water. Oliver (3233) filtered crude ammoniacal gas liquor wastes through clinkers after diluting the waste with domestic sewage. Kabakova and Vil'gel'mov (2361) stated that biological purification of phenolic waters from coke ovens and gas plants in combination with domestic sewage was advantageous, provided the relative amounts of phenolic waters were small and the recovery of phenol was uneconomical. Bach (118) purified phenol waste biologically following dilution of the waste with final effluent.

The removal of tars prior to biological treatment was a prerequisite, as suggested by Mihail and Popescu (2998) where preliminary acidification followed by sedimentation and filtration through scrap iron or coke was used. Phenols were removed on a slag trickling filter. Drabek (1023) removed tar in a sedimentation tank, followed by filtration through a coke filter, and the subsequent spraying of the waste over the surface of a slag filter. Abson and Todhunter (7) described a three-stage process for treatment of coke oven effluents as (a) phenols and higher tars were removed by an activated-sludge process, (b) thiocyanate, thiosulfate and cyanide were subsequently removed by biological filtration, and (c) ammonia was then removed by nitrifying bacteria in sludge tanks. Solin (4105) obtained improved filtration of gas generator effluents on slag filters after preliminary detarring of the waste water.

The preconditioning or acclimatizing of the biofilm on trickling filter media with municipal sewage prior to the introduction of phenolic wastes was recommended by Zdybiewska (4852). Preconditioned blast furnace slag was used with municipal sewage before introducing phenolic waste waters from coking plants for treatment. Zdybiewska and Bursztynowicz (4854) conditioned blast furnace slag with municipal sewage for ten days and gradually increased the amounts of phenolic wastes. Nellist (3158) noted that coke works liquor could be treated on trickling filters if combined with domestic sewage. Additional filter capacity was not required (3158), with only slight deterioration of effluent quality. Norwood and Schaeffer (3205) recommended passage of phenolic waste waters through retention ponds before filtration. Barritt et al. (198) described the pre-use of effluents from condensate plants in a coal washery and froth flotation plant. Final reduction of the phenol was obtained by biological treatment in an activated sludge plant, and trickling filters were cited as a possibility. Hsu et al. (2074) obtained partial removal of phenols upon pretreatment of the waste through storage and aeration, but most of the removal was obtained by subsequent trickling filtration.

Coke and gas plant wastes have also been preconditioned for biological treatment by chemical extraction of the phenolic compounds. Johnson (2325) purified a phenolic waste by first extracting the phenol, aerating the liquid, and finally subjecting the waste to biological treatment on a trickling filter. Prüss (3472) removed most of the phenol from a coke plant waste by extraction. The unextracted phenol was destroyed biologically by acclimatized filter beds or activated sludge. Key and Etheridge (2464), however, found no advantage in the pretreatment removal of phenol from spent and ammoniacal liquors before treatment with municipal sewage on trickling filters or activated sludge. Putilina (3487) removed phenol, sulfur, and cyanide compounds from undiluted waste water by means of special bacterial cultures followed by biological filtration. Reich (3532) used pretreatment which consisted of neutralization, sedimentation, and phenol extraction, with the phenolic effluent combined with domestic sewage and treated with a biological filter.

EFFICIENCY OF TRICKLING FILTER APPLICATIONS

Biczysko (321) reduced the phenol content after first-stage filtration by 56-70%. Bryan (516) also reported a 50-75% reduction in a first-stage treatment and an overall efficiency of 95% in combination with activated sludge. Noble (3194) obtained an efficiency of 93-95% from a liquor containing 3,000-5,000 mg/l total phenols in a two-stage treatment. Jenkins et al. (2296) obtained a higher treatment efficiency for domestic sewage combined with coal carbonization plant effluents than with domestic sewage alone. Phenol was reduced from 1,190-3,150 mg/l to 0.2-5 mg/l in a two-stage biological process. Porter and Dutch (3437) obtained 95% reduction in phenol and 90% reduction in cyanide from coke oven waste using a plastic trickling filter medium.

The efficiency of treatment as a function of the initial concentrations of components was observed by Zdybiewska and Bursztynowicz (4854) where a reduction in phenolic content of 98.6% was obtained on blast slag. This waste contained 100 mg/l of total phenols in combination with municipal sewage. Drabek (1022) treated waste waters from gas works containing 843-951 mg/l of monohydric phenols and 353-392 mg/l dihydric phenols and found no phenols in the filtered water during the first six months of operation. Eventually, 11.7-172 mg/l of total phenols were found in the effluent in the following nine months of operation. Specific active strains of bacteria removed 96% of the phenolic compounds from a gas condensate waste containing 2,000 mg/l of phenolic compounds, according to Husmann and Malz (2154).

Some authors had reported effective treatment on undiluted gas and coke plant wastes, but most agreed that some preliminary dilution was required for effective treatment. Gwilliam et al. (1635) found that concentrations of 20-40 mg/l phenol were completely destroyed during biological filtration, but an upper limit of phenol concentration existed which could be treated satisfactorily. The actual limit was not determined, but a filter charged with 200 mg/l phenol became choked with black septic matter and could not oxidize the phenol completely. Biczysko (320) conducted experiments to verify the efficiency of deep bed filters and the oxidation available for the treatment of phenolic waste waters.

COMPARISON OF TRICKLING FILTERS WITH OTHER METHODS

Sherwood (3994) reviewed and compared the treatment of phenolic waste waters from gas producing plants by the activated-sludge process and by the trickling filtration process. Bischofsberger and Wurm (335) described the treatment of phenolic waste waters by biological processes using activated sludge, trickling filtration, and both processes in series. Bandt (161) described the treatment of phenolic waste waters by both trickling filtration and by activated sludge. Velek (4532) described various methods of removing phenols from waste waters, e.g., biological filtration, ion exchange, and adsorption. Knop (2525) stated that residual phenol in coke works waste waters may be destroyed by treatment in either trickling filters or activated sludge. The advantages of plastic trickling filtration media for treating phenolic wastes over other materials (crushed stone, clay blocks, or Raschig rings) were discussed by Bryan (514). Husmann and Malz (2154) found that phenol-containing sewage was successfully treated by both trickling filtration and activated-sludge processes. The best treatment was accomplished with the aid of very active strains of bacteria together with long aeration.

There was disagreement in the literature as to whether the trickling filter or activated-sludge process was preferred for coke and gas plant waste treatment. Noble et al. (3193) found that the power requirements for the activated-sludge treatment of gas liquor wastes, as in municipal works, were more than for packed towers. A longer period of acclimation, less space utilized, and less sensitivity to change were attributed to the packed towers (3193). Norwood and Schaeffer (3205) agreed that the activated-sludge process was more sensitive to shock loadings and variations in feed concentration, whereas trickling filters were considered (4948) much more resilient to sudden changes in loading. An effluent containing 20% of the "devil" liquor from a coke oven operation was treated satisfactorily with trickling filters, while only 2% was treatable using an activated-sludge process. Investigations (4947) have shown that percolating filters could be used instead of aeration tanks and were more suitable for certain of these trade effluents.

In some instances, the activated-sludge process has been preferred to trickling filtration as a result of comparisons at various flow rates of coal carbonization waste waters (3622). In another instance, effluent from a coke works was successfully treated by the activated-sludge process but an enclosed trickling filter was not successful (5033). Nellist (3158) reviewed previous studies and stated that the activated-sludge process was successful in treating coke works wastes but that percolating filters treating the same wastes were observed to age. This aging was apparently a result of choking of the filter medium with sludge and not due to a filter for growth development. This author reported that trickling filters were successful in treating up to 2% coke waste liquor in combination with sewage. Prüss (3470), in an earlier paper, described the treatment of phenol-containing effluents by sprinkling filters and by activated sludge. Costs for the sprinkling filters at that time were considered too great. The activated-sludge process was reported to be better suited for the varying composition of the phenolic waste.

Chemical methods for the destruction of toxic components in coke and gas plant effluents have also been described by Abson and Todhunter (6). These included oxidation by ozone, nitrous or nitric acids, chlorine, treatment with formaldehyde, lime, or sulfuric acid, and ion exchange. Microbiological processes, including trickling filtration and activated sludge, were compared with chemical methods. Savage (3832) described studies on the treatment of ammoniacal waste waters by biological filtration and by oxidation with chlorine dioxide. Neither method was entirely satisfactory and a countercurrent extraction of phenols was employed, followed by distillation of ammonia before discharge.

Bulicek (528) reviewed methods of removing phenol from waste waters which included the preparation of fertilizers, combustion, evaporation, use in coke-quenching and coal-washing, sedimentation, filtration, chlorination, adsorption on activated carbon, steam distillation, extraction with hydrocarbons, oxidation, and precipitation. Bulicek reported that the most common methods for treatment were oxidation, filtration, precipitation, and extraction. Sherwood (3994) also reviewed existing methods for the treatment of phenolic waste waters from gas producing plants. These (3994) included air flotation, evaporation, and catalytic oxidation. The intense taste and odor produced by phenolic compounds were recognized (3994) as a severe problem. Abson and Todhunter (6) described the recovery of phenols from carbonization effluents by three main methods: distillation and absorption or adsorption of phenolic vapors, direct adsorption, and solvent extraction.

POST-TREATMENT

Post-treatment of coke and gas plant wastes initially treated by trickling filtration has usually consisted of a second-stage biological treatment and sedimentation to remove sludge. Bryan (516) described two-stage biological treatment of phenolic waste: a first-stage trickling filtration was followed by a second-stage activated-sludge process. Meissner (2961) also used staged treatment of coal waste containing phenol and ammonia. The final stage was biological treatment by trickling filtration and activated sludge. Malz (2855) recommended a two-stage trickling filtration or activated sludge process in which the stages were operated at different temperatures (18° and 55° C) conducive to the growth of mesophilic and thermophilic organisms.

Studies were carried out on the removal of the "intractable residue" which remained in coke and gas effluents after biological treatment. This residue was removed by passage of the effluent from biological treatment through a bed of suitable ion exchange resin (5607). In the treatment of coke oven effluents described by Abson and Todhunter (7), phenol and tars were removed in an activated-sludge process, thiocyanate, thiosulfate and cyanide by trickling filtration,and the ammonia was subsequently removed by nitrifying bacteria in sludge tanks. Suszka (4270) investigated the purification of coke plant wastes containing phenolic compounds by primary sedimentation and trickling filtration followed by pond oxidation, secondary sedimentation, and sludge recirculation.

SPECIAL OPERATIONAL PROBLEMS

Blackburn and Kershaw (347) described the treatment of gas works and coke oven liquors in admixture with sewage on trickling filters. Considerations of the volume and height of the packed filter to reduce the "end" and "wall" effects were discussed by Noble (3194). DeLaporte (921) emphasized the segregation and separation of phenolic waste for treatment to prevent pollution by the waste water.

Noble et al. (3193) observed some difficulty in settling biological solids in the effluents of gas liquor wastes treated with trickling filters. This problem was overcome by adding chlorinated copperas or by returning settled sludge to the aeration tanks. Stewart (4217) stated that the presence of phenol reduced the proportion of BOD removed in settling tanks. Phenol remained in solution but was decomposed under aerobic conditions in a trickling filter and no phenol reached the sludge digestion tanks.

The concentration of pollutants and the degree of dilution required as well as other operational parameters were considered by Kucharski (2583). Porter and Dutch (3437) reported that sulfides in concentrations up to 50 mg/l had a negligible effect upon the operation of plastic trickling filters used in treating coke oven wastes. Hsu et al. (2074) emphasized the necessity of supplying inorganic nutrients as well as maintaining optimum oxygen content to promote the vigorous growth of organisms that degraded phenolic wastes.

Biczysko (321) noted that the efficiency of treatment of phenolic waste waters on trickling filters decreased with increased temperature up to 43-46°C, then increased to a maximum at 55-60°C, and decreased again at higher temperatures. Taubert (4308), however, recommended an optimum temperature for treatment of gas works effluent in the range of 20-25°C. The effects of temperature, loading rate, biological growth, and nitrogen balance on the rate of phenol removal were observed by Malz (2855). Husmann and Malz (2151) discussed the importance of the growth of mesophilic and thermophilic organisms for biological filtration of phenolic wastes.

The use of slag filters stimulated considerations of adsorption and biological oxidation. Solin et al. (4106) observed that some cresols were adsorbed on slag in a manner similar to the adsorption of phenol and pyrocatechol. These adsorbed phenolic compounds were then subsequently oxidized into substances which condensed to form humic acids. Solin and Erlebach (4103) stated that the adsorptivity of phenolic compounds onto slag depended upon the load and period of use of the filters. Solin et al. (4102) also described the satisfactory performance of slag filters even without sufficient aeration to oxidize phenols to form humic substances. Kres (2568) indicated that activated carbon was a suitable material for purification of phenolic wastes for special cases such as drinking water supplies.

The character of the microbial populations growing upon trickling filters has been described in other sections of this review. Zdybiewska (4853) observed that the population of living organisms was greater in the upper layers of trickling filters and increased with increasing concentrations of phenols in the waste treatment. Palaty (3274) inoculated a trickling filter with the fungus Oospora and used this unit to treat generator waste waters containing phenols. Jenkins et al. (2296) observed some adverse effects upon nitrification and the responsible organisms following treatment of coke carbonization plant effluents by biological filtration.

Critique

General observations on the operation of trickling filters for the treatment of coke and gas plant wastes have been primarily concerned with the nature and the concentrations of the components of the waste treated, the temperature of operation, and the effect of trickling filtration upon subsequent treatment processes, such as adsorption and nitrification.

Satisfactory treatment by trickling filter and activated sludge individually and together was reported to the extent that a clear choice is not obvious. A major difficulty is that most of the literature dealt with "phenolic wastes" --

a term which is not really very descriptive. Toxicity factors were present in some waste streams and absent in others. A comprehensive piece of work outlining all the ramifications of gas and coke plant wastes has on occasion been undertaken, unfortunately, for a specific plant, location, or agency. It would appear from this review that one may use trickling filters, after some pretreatment, to purify these wastes. If a high quality effluent is required, staged operation should be used whether it may be another filter or activated sludge. The economics of a particular situation may aid in making the decision. Systems other than biological treatment have been fully explored and evidently found economically inferior.

SECTION XXI

FOOD PROCESSING WASTES

Food processing wastes as used in this section are defined as wastes from edible food processing other than meat wastes.

A history of the use of biological trickling filters and other methods for the treatment of canning waste was published by Murphy et al. (3133) in 1928. Food industry wastes were classified by McLachlan (2930), in which it was generalized that these wastes were treated by screening, sedimentation, chemical treatment, and biological fermentation. Typically, the reviews and symposia which have been held to deal with the problem of food processing waste waters (4956, 5589) involved various conventional and novel methods of biological treatment. Hemens (1875) and Loesecke (2750) have characterized food processing wastes and reported treatment methods, including biological filtration.

Alternative methods available to the designer and contractor of waste treatment plants handling food processing wastes were published in 1931 by the New York State Department of Health. Heider (1855) reviewed the canning industry in the state of Indiana and found that there were 235 installations in 1945 which produced waste water having an organic content with the equivalent of ten times that of domestic sewage. The seasonal operation of the canning industry has been a continuing waste treatment problem (1855, 4332). Trade groups such as The National Canners Association outlined the properties of waste waters from canners and reviewed earlier methods of treating these waste waters (4619).

The facilities for the treatment of corn and soybean wastes of the Decatur plant of A. E. Staley Company, which was reviewed by Willenbrink (4734), had a population equivalent of 220,000 to 230,000 per day. Imhoff tanks, percolating filters and lagoons plus contact-stabilization plants were used for treatment. Pearse and Greeley (3319) used an experimental sprinkling filter plant to handle corn products and gas works waste. A typical problem at many food processing effluent treatment plants was maintaining adequate flow during off-seasons, while at the same time having sufficient capacity for the canning season (531, 5646). The high-rate biological filtration plant in North Davis County, Utah, described by Templeton (4338), maintained satisfactory performance in spite of the variety of cannery wastes being treated. The wastes from cucumber (2481) or pea and bean (162) canning and dehydration of various foods (924) were all biologically treatable, usually on recirculating high-rate filters.

Literature in 1960 by the U. S. Public Health Service (5594) characterized several food processing wastes, such as potato

Preceding page blank

chip wastes. Characteristics dealing with pH, population equivalent, solids and permanganate values were reported by DeMartini et al. (924) for several vegetables and milk product materials. Buzzell et al. (572) characterized potato starch waste. Typical food and fermentation waste strengths were tabulated by Dlouhy and Dahlstrom (983) and advantages of primary, secondary, and tertiary treatment were considered. General aspects of industrial waste treatment and uses of trickling filters for treating waste from canneries were outlined by Eldridge (1141), where recirculating trickling filters, loaded with over 1 lb BOD/yd^3 of medium per day (37 lb of BOD/1,000 ft^3/day) at the rate of 15 to 20 mgad (345 to 460 gal./ft^2/day), achieved the desired BOD removals.

Loesecke et al. (2749) reported on experimental treatment of citrus cannery effluent, where the influent BOD varied from 100 to 1,400 mg/l and contained inorganic salts, organic acids, pectin, and sugar with very low nitrogen content. Domestic sewage flow of 750,000 gal./day and about 300,000 gal./day of waste waters from processing fruit and vegetables were reported to have a BOD varying from 220 to 1,230 mg/l and to contain 30 to 363 mg/l suspended solids (1952). The BOD of a fruit processing plant making apple butter and preserves was reported by Hommon (1991) to be 600 mg/l. Tomato canning waste was described by Hert (1900) to have a BOD of 548 mg/l, 1,341 mg/l total solids, 275 mg/l suspended solids, and 1,064 mg/l dissolved solids, while pumpkin canning waste had an average BOD of 4,606 mg/l to contain 10,609 mg/l total solids, and 1,103 mg/l suspended solids (1901). The characteristics from a vegetable and fruit canning factory were reported by Miller and Clark (3009) to be 50,000 gal./30 tons of vegetables/day, to have a high pH, and to have a tendency to pond trickling filters. The wash waters of the first washing from production of dried vegetables were large in volume, but not very polluting, and after sedimentation the BOD usually ranged between 10 and 6 mg/l. Waste waters from the peeling process had a BOD of 300 to 2,000 mg/l, and from the blanching process had a BOD of from 5,000 to 15,000 mg/l, with their volume usually less than that of waste waters from preliminary washing or from the peeling process, according to Jones (2337).

Successful use of biological filtration after screening and sedimentation was reported by Pettet (3347) on grain processing waste waters which were characterized to have a maximum of 4,470 mg/l BOD and 2,190 mg/l COD. The usual waste volumes were from 47.5 to 175 gallons per quarter of wheat washed with clarified BOD of 0.39 to 0.48 pound per quarter of wheat (3347). An edible oil refinery effluent was characterized by Cunningham (843) to be approximately 200 gal./min, a BOD of approximately 1,000 mg/l and a high fat content. The BOD of corn canning waste waters varied from 1,200 to 4,000 mg/l and total solids from 1,500 to 8,000 mg/l with total volatile solids from 1,400 to 7,000 mg/l, and suspended solids from 300 to 4,000 mg/l, as reported by Halvorson et al. (1673). Horton et al. (2039) reported on the waste water characteristics in coffee production and stated that the waste volume varied from 100 to 260 gal./100 lb of coffee beans produced and the fermentation waste waters had a BOD of 1,700 mg/l and 900 mg/l suspended solids with 2,100 mg/l total solids.

PRETREATMENT REQUIRED

Eldridge (1144) surveyed the application of chemical processes in industrial waste treatment, specifically noting the utility of these processes in the seasonal discharge of cannery waste and the use of chemicals for pretreatment such as lime, ferrous sulfate, alum, ferric chloride, ferric sulfate, or zinc chloride. Slow settling of the solids was an objection (2039) to some chemical coagulants. The Ohio Canners Association (2484) reported in 1926 that biological filtration was an effective method for treating vegetable processing waste waters at the rate of 2 mgad (46 gal./ft^2/day) and suggested pretreatment of these wastes to include sedimentation using lime or sodium aluminate, pH adjustment and chlorination. From pilot plant studies to determine the loading rates and media requirements for the treatment of several food processing wastes, for the Indiana Canners Association, Miller (3007) concluded that tomato wastes could not be clarified without the addition of chemicals such as lime and ferrous sulfate. Investigations by Warrick (4614) on pea cannery wastes indicated that 75% removal could be achieved by chemical treatment and, therefore, 33 Wisconsin canneries installed this process, as of 1934. However, treatment of beet and carrot cannery waste on trickling filters at municipal sewage works had been proven satisfactory (4614).

Humphrey (2087) reported, in 1940, that canning wastes often needed separate treatment if the cannery was not near a sewage works of sufficient size which could handle the effluent. Waste waters from the production of sauerkraut were reported by Tänzler (4290) and Haseltine (1786) to contain lactic acid, sodium chloride, and protein compounds with a high sulfur content and which was treated by hot lime to neutralize the pH (6.6 required) prior to discharge to sewers and biological treatment. Wastes from tomato canning caused difficulties in a septic tank trickling filter, plant, were treated with lime at 1 pound per 500 gallons waste (2087), and then successfully treated by a settling tank trickling filter (1065). Ventz and Zaenger (4537) treated fish processing waste water with ferric chloride to break the fat-protein emulsion prior to biological filtration.

Satisfactory results were obtained by Hatfield et al. (1793) for the treatment of corn wastes when the pH value of the effluent was between 6.0 and 8.5, the ratio of the recirculated filter effluent was constant, and the ratios of BOD to nitrogen of 20:1 and of BOD to phosphorus of 75:1 were maintained. Pearse (4214) outlined the characteristics of corn product waste and general method of treatment and noted that if the wastes were diluted four times with condensed water they could be treated on trickling filters at 0.7 mgad (16.1 gal./ft^2/day).

One sugar factory (3284) treated their waste by aeration and biological filtration followed by a 1 to 10 dilution (Shukla Process). McLachlan (2930) stated that balancing tanks should be used ahead of the trickling filters to maintain a constant load on the filters. Acid fermentation might occur in the waste before it reached the filters and was counteracted by the addition of lime and chlorine (2930) or recirculation of treated effluent (963). A segregated high strength citrus waste was reported by Kimball and Furman (2483) to be pumped directly to the municipal waste treatment plant and a combination of domestic sewage and citrus waste mixed in a ratio of 1:1 was successfully treated biologically.

Pretreatment by roughing filter or preaeration was advisable in treating waste from a margarine factory with high-rate percolating filters in combination with activated sludge and also by alternating double filtration (2415). A high-rate filter installed ahead of the standard rate filter to remove a large portion of the BOD was a typical plant modification, where the standard rate trickling filter plant was overloaded, according to Moyer (3108). Hatfield (1796) reported, in 1928, that activated sludge operated between an Imhoff tank and trickling filter relieved the overloaded conditions from a corn products factory to the point that the filter capacity was increased three or four times. The "bottled-up" system of corn processing, which employed reuse of waste water, drastically reduced the pollution load (1574).

Anaerobic fermentation was used successfully at a Florida installation on citrus fruit canning waste prior to biological filtration to remove compound toxic to fish and eliminate odor problems (5153). Methane produced in the process was used as a source of fuel to aid in lowering the cost of treatment. Both biological filtration and anaerobic digestion considerably reduced the pollution load of starch wastes, but were not truly satisfactory for the conditions required, according to Stander and Gien (4177).

EFFICIENCY OF TRICKLING FILTER APPLICATION

The typical effect that a canning waste would have on a municipal waste treatment plant indicated (3087) that when sewage alone was treated the BOD was reduced from 320 to

21 mg/l and when cannery wastes were treated in combination the BOD was reduced from 1,566 to 466 mg/l and the suspended solids were comparably affected. Treatment of the pea canning waste on trickling filters, after screening, removed 80% to 95% of the BOD when the filters were operated at 0.5 mgad (11.5 gal./ft^2/day), which was sufficient if the final dilution was not less than 5:1 (2486). By quadrupling the hydraulic load, the percent BOD removed dropped to 50 to 70%, and required a final dilution of at least 20:1. Dickinson (964) concluded that food processing wastes were amenable to treatment in percolating filters when an influent BOD of 1,140 mg/l and a 4-hour oxygen demand of 472 mg/l were reduced by filtration to a BOD of 3.5 mg/l and an oxygen demand of 3.6 mg/l.

Treatment of malting and cannery wastes by dipping contact filters was reported by Hartmann (1773) to produce 60% BOD removal on the filter with the remaining being removed in a post-treatment aeration tank with a retention period of 20 minutes. Food processing wastes were treated by a 1.5 mgd (39.5 gal./ft^2/day) trickling filter plant to produce 80 to 85% removal of settleable solids and 95% removal of BOD, according to Hill (1952). Crawley and Brouillette (815) reported BOD and average suspended solids removal of about 53% and 59%, respectively, on PVC roughing filters from the frozen food processing industry wastes. Several reports (2039, 2749, 3284) indicated that food processing wastes could be treated on biological filtration systems, with and without recirculation, to attain reductions in BOD in the high ninety percent range.

According to a paper by Young (4844), a sewage flow of 200,000 gal./day increased to 380,000 gal./day during the cherry canning season, when the influent BOD was 840 mg/l and final effluent was 350 mg/l. Chemical treatment with lime and copperas reduced the BOD to 382 mg/l and coagulation of cherry or tomato canning wastes with alum could reduce BOD by as much as 50%. Kruse (2578) removed 80% of the polluting load, as measured by the permanganate and BOD values, using a high rate percolating filter to treat fruit packing waste at 1,000 to 2,500 grams of BOD/m^3/day (6.2 to 15.5 lb of BOD/1,000 ft^3/day).

Sedimentation reduced (2337) the suspended solids from dried vegetable production by 76%. However, the BOD of 310 mg/l from the preparation of potatoes was 330 mg/l after sedimentation. When carrots were being prepared, the BOD change due to settling was reduced from 1,220 to 860 mg/l. The oxygen absorbed permanganate value in 4 hours was 144 mg/l before sedimentation and 76 mg/l after sedimentation for potatoes, and 940 mg/l before sedimentation and 810 mg/l after sedimentation for carrots (2337). In experiments by the Wisconsin State Board of Health (5090), pretreatment involved chemical precipitation with lime and ferrous sulfate which reduced a composite beet canning waste by 96% suspended solids and 50% BOD, and a carrot canning waste by 98% suspended solids and 67% BOD. These wastes (5090) were discharged to the municipal trickling filter plant which produced an effluent containing 82 mg/l total solids and 57 mg/l suspended solids and 88 mg/l BOD.

Waste liquor from a tomato canning plant which had primary treatment was combined with domestic sewage by Hert (1900) to remove 11.9% of the BOD, 41% of the suspended solids and, after the tomato waste was applied to percolating filter at 0.724 lb BOD/yd^3/day (26.8 lb BOD/1,000 ft^3/day), 70% BOD was removed, producing an effluent with 161 mg/l. A high-rate percolating filter added to an overloaded tomato cannery waste treatment plant was loaded (1934) at about 510 lb/day and 55% BOD was removed by the percolating filter after sedimentation. A recirculation ratio of 4.5:1 was used in the treatment of blancher waste water from a pea cannery (2669) to produce an overall BOD reduction of 78.8%. Hert (1901) stated that 25% of the BOD and 58% of the suspended solids were removed in primary treatment from pumpkin canning waste water admixed with domestic sewage, and with biological filtration 74% of the BOD was removed, producing an effluent of 965 mg/l when loaded at 1.232 lb/yd^3/day (46 lb BOD/1,000 ft^3/day).

Fatty waste waters from a vegetable oil refinery and a chemical plant were treated on packed towers, where the BOD was reduced from 5,000 to 50 mg/l and the pH increased from 1.5 to 7 (3276). Eighty-three percent of the organic contaminants were reported by Ventz and Zaenger (4537) to be removed from a fish processing waste water, where ferric chloride was added to break up and precipitate fat protein emulsions and the effluent was treated by biological filtration and lagooning.

Pilot plant studies were made by Haseltine (1786) on the treatment of waste waters from kraut and pickle manufacture by biological filtration and the maximum efficiency was estimated when the BOD of the recirculated effluent was less than 40% of the total BOD applied to the filter, i.e., a recirculation ratio of not more than 7. BOD removals of 85% were obtained from the kraut and pickle waste liquors on a pilot plant filter containing blast slag with no correlation between recycle ratio and BOD reduction observed.

One sugar refinery increased removal of organic matters from its wastes from 70% to more than 90% by the addition of a percolating filter and final clarifier (1308). Another plant (2149) experienced difficulties because of rapid fungi growth on the filters, although 75 to 95% purification of the sugar waste was obtained. Brandon (444) reported on methods of treatment of waste waters from processing coffee, which were equivalent in polluting character to about 60,000 gallons of domestic sewage for each ton of clean coffee produced. Biological filtration was satisfactory, contrary to the experience of Chalmers (647), to treat the mixed waste waters (BOD of 1,100 to 1,800 mg/l) which were diluted four times by filter effluent and applied to the filter at the rate of 100 gal./yd^3/day (11.1 lb BOD/1,000 ft^3/day) from which the settled effluent had a final BOD of 17 to 104 mg/l.

Plastic media biological filtration systems treating various food processing wastes were reported (98, 643, 678, 2972, 4084, 5196, 5325, 5330) to be economically successful and highly efficient. These systems treated a variety of fruits and vegetable wastes without the use of polyelectrolyte flocculants and satisfactory operation was achieved as an economic solution to the high BOD waste. A plastic media trickling filter, which also doubled as a cooling tower for a corn steep process and a vegetable oil refinery waste, was described in a paper by Bryan (516). About the same time, Hamlin (1697) described a super-rate biological filter with a cellular clay pipe medium to successfully treat fruit and vegetable cannery wastes. The filter had good resistance to shock loads and the performance has been excellent. Rock trickling filters were included in a discussion of food processing waste treatment methods by Rudolfs and Heukelekian (3772), and later Chipperfield (674) compared synthetic filter media with conventional media.

COMPARISON TO OTHER METHODS OF TREATMENT

Siebert and Allison (4016) discussed several examples of typical plants used to treat waste waters from canneries. Chemical addition with lagoons, screening with sand filtration and with chemical addition, percolating filters followed necessarily by large lagoons, storage, and again large lagoons was discussed (4016) with regard to inherent limitations and advantages of these installations. Mercer and Rose (2973) investigated high-rate trickling filters, air flotation, circular vibrating screens, and chemical addition to treat food processing wastes. Alternative methods were discussed by Wakefield et al. (4570) for the disposal of citrus waste and the recovery of byproducts, for example, lagoons, discharge to municipal sewers, and the activated-sludge process were commonly utilized. Several methods of cannery waste treatments, such as lagooning, biological filtration, coagulation and disposal by spray irrigation, were compared by Anderson (74) in 1967.

Chalmers (647) described the treatment of waste waters from coffee manufacturing which had a BOD of from 6,000 to 8,000 mg/l and alternative methods of treatment, such as activated sludge and trickling filters as well as physical removal, were evaluated. Physical removal involving screening, centrifuging, filtration, evaporation of selected strong liquors and incineration was determined to be the most economical.

Comparison of chemical treatment with ferrous sulfate and lime with biological trickling filters was made by Warrick (4615). The chemical treatment reduced the oxygen demand by 50 to 75% and the trickling filter reduced the oxygen demand by 76 to 94%. The BOD was reduced by 70 to 92% when sweet pea canning wastes were chemically treated and applied to the filter at rates below 3 mgad (69 gal./ft^2/day), but the efficiency was slightly reduced when screened waste was applied at rates of 1 to 2.1 mgad (23 to 48 gal./ft^2/day). Jones (2338) experimented with treatment of cider waste admixed with domestic sewage on single stage filtration, with and without recirculation, and with alternating double filtration. The most satisfactory method was by single filtration with recirculation of the effluent and special attention was paid to the nitrogen deficient nature of the waste. Recirculation of the effluent was employed and a diammonium phosphate nutrient was added to a plastic media filter for which BOD and COD removal was three times greater than that reported for conventional filters (5324).

Standard and high-rate percolating filters were compared by Buzzell et al. (572) with activated-sludge units in the treatment of synthetic protein water and that from a potato starch factory. Activated sludge removed 95% of the BOD with loadings up to 80 pounds of BOD per 1,000 lb of mixed liquor-suspended solids per hour of aeration. Standard rate filters loaded up to 1,300 lb of BOD/ac-f/day (29.9 lb of BOD/ 1,000 ft^3/day) removed 90%, as did high-rate filters loaded up to 300 lb/ac-f/day (69 lb/1,000 ft^3/day). Wakefield (4571) reported in 1954 that citrus fruit waste water could be processed satisfactorily by high-rate biological filtration and by the activated-sludge process, but both required nutrient supplement. As alternatives, if sufficient land is available, spray irrigation was satisfactory, but chemical coagulation with air flotation was not satisfactory.

However, it was suggested by Kammann and Herb (2375) in 1930 that activated-sludge treatment was replacing biological filtration to the point that it was not to be considered as an economical means of treatment. Likewise, an Imhoff-trickling filter plant was modified in favor of activated sludge in 1928 for treating corn product wastes at Decatur, Illinois, due to the added expense and equal operating efficiencies (5365). In contrast, Pearse (4214) considered both systems for comparing the treatment of corn product waste and activated sludge as not being successful. Norgaard et al. (3200) reported, in 1960, on the experience of a pilot plant composed of activated sludge and high-rate biological filtration. From the results obtained by the prototype, the projected area required for handling the cannery waste waters was excessive and disqualified the use of high-rate filters.

POST-TREATMENT AND EFFLUENT QUALITY

Typical of examples of post-treatment was a California sewage treatment plant which installed high-rate biological filtration followed by extensive post-treatment to cope with a 76% increase in food processing wastes over a period of five years (645). Warrick et al. (4621) described their studies on the disposal of cannery waste waters by discharge to lagoons, and for many wastes lagoons are a partial solution to cannery waste disposal problems with the limitation being control of odors and the large area required. Waste disposal methods of solid and liquid waste from food canneries were discussed by Wisniewski (4797) with strong emphasis on the economic nature of the problem. The seasonal factor of the canning industry gave rise to the use of land disposal screening, biological filtration, chemical precipitation and lagooning, and discharge to municipal treatment (3816, 4797).

Henry et al. (1883) reported in 1954 on the disposal of biological filtration effluent on crop irrigation systems and it was found that Reed canary grass, which was tolerant to wet conditions, would accept 40 inches or more of water applied during the growing season (May to October). Almost all of the nitrogen, phosphorus, and potassium were removed from the effluent by the crops in the soil. There was no evidence of bacterial pollution of a nearby creek as a result of drainage from the area, but concentrations of sodium and chloride in the creek water were increased.

SPECIAL OPERATIONAL PROBLEMS

Fifteen pounds of chlorine were applied daily to a flow of a little over a million gallons per day consisting of domestic sewage and fruit processing wastes to combat problems arising from odors during the summer and autumn (1906). Problems with foaming and flies on a trickling filter handling corn packing plant wastes were solved by the addition of hypochlorite to the filters, and chlorination of the effluent allowed it to be discharged into a small stream and lake (4884). Corn sugar refinery steep water was shown (3669) to be a possible source of nitrogen for the fermentation of alcohols from waste sugars which left almost a stable final waste. A possible use for waste molasses and yeast was composting vegetable matter to give a higher nitrogen content than with molasses alone, which would be an attractive proposition for cane growing countries with surplus molasses and a limited demand for alcohol (1955).

Typically overloaded conditions were reported (5640) in 1965 for Cambridge, where the biological filtration plant was inadequate to handle the increased domestic sewage waste waters plus waste discharged from a jam and other cannery factories. To alleviate this condition, modifications were made which included additional percolating filters with recirculation and other appurtenances. Mangold (2856) described experiments in which wheat starch wastes were treated on an enclosed percolating filter with artificial aeration. The treatment was satisfactory, but the cost of treatment would be high.

In 1968, Koehler (2538) described possible treatment methods for the problem of seasonal wastes from sugar, potato, and sauerkraut processing plants. Shallow ponds were considered along with their disadvantages, as well as successful application to trickling filters. Segregation of the waste waters from domestic sewage and cannery waters was practiced in Australia, according to Furphy and Ley (1386), to avoid treatment plant operating problems due to alkaline peach or acid pear canning wastes.

Infiltration of oil and washing waters from hangars and restaurants was reported by Kelez (2422) to be a chief operating difficulty for trickling filter operation at an airport location. The primary problem in wastes occurring from the preparation of foods at restaurant facilities along turnpike installations (5403) was grease, which, once removed by means of a preliminary digester, allowed the percolating filters to operate with recirculation of chlorinated effluent.

Culp (838) reported in 1963 on laboratory and pilot plant studies treating mixtures of domestic sewage and cannery wastes on a system which involved chemical coagulation, primary adsorption on alum, rapid filtration, followed, when necessary, by secondary adsorption on activated carbon. Biological trickling filtration was not used in this process; however, the principal disadvantage of the process appeared to be high operating costs due to the cost of chemicals and skilled operation. Thus, because of economics the problem of treating waste is forced back to conventional methods.

Critique

The large quantity of literature available on biological filtration of food processing wastes is indicative of the successful use of this method of treatment. Since most food waste waters contain organic matter in varying degrees of concentration, with at best intermittent flow and, more importantly, increased seasonal discharges, elevated temperatures, alkaline and acid conditions, as well as other factors, pretreatment of the waste waters was determined to be of considerable importance in this application. The sources of these waste waters came from washing, cutting, peeling, juicing, blanching, pasteurizing, maintenance of equipment, and other water-using procedures. Information regarding the characteristics, sources and treatment of food processing wastes has been reported in considerable depth in several industrial waste treatment texts, e.g., "The Treatment of Industrial Waste," by Besselievre (308).

Much of the literature showed that on similar studies similar conclusions were reached at essentially the same time. This observation indicated poor communication, or awareness on the part of the investigators, or doubt of the validity of the previous work. Most of the literature appeared to have been developed from a "make do" motivation for situations requiring attention. Much of the published information informed the public that a waste treatment plant was constructed and was operating properly except for a few minor problems. Some design information was available and, as more reports were made on operational experience, these data were also used for design. It must be pointed out that discrepancies in results reported in this review on apparently identical waste streams may, in actuality, support rather than refute the conclusions of the investigators. The reason for this conflict is that one tomato canning waste or coffee processing plant effluent may, quite conceivably, be significantly different from another similar waste. This statement is not meant to imply that generalizations are impossible or to be discouraged, but that conflicting conclusions should be appreciated.

In summary, biological filtration has been shown to be partially effective for the treatment of food processing waste. Considerable pretreatment was reported to aid materially in producing an efficient waste treatment system. In comparing biological filtrations with other methods, certain waste and conditions arose which favored the other methods. However, quite often biological filtration was an economical means of waste treatment. As an aid to provide this economic incentive, low cost, high performance synthetic filtration media were introduced for the treatment of high BOD waste, such as that found in food processing effluent. Post-treatment of trickling filter effluent,other than the more conventional secondary settling tank and chlorination,has been extensive use of lagooning. Most operational problems have evolved around nuisance conditions common to percolating filters, such as odors, ponding, and fly production. Each of these problems has had many answers proposed and applied to make the process or biological filtration acceptable for the treatment of food processing waste.

SECTION XXII

INSTITUTIONAL AND MILITARY WASTES

The waste waters from institutional and military sources are unique because they closely approach the characteristics of domestic sewage, with possibilities of having high grease and oil content and producing flows of extreme variability. It was estimated in 1955 by Thompson et al. (4379) that 78% of the air bases in the United States treat their own sewage, while 20% of them discharge to nearby municipal installations and 2% discharge untreated sewage to receiving bodies of water (4379). Much of the design and operational experience in 1941 for the operation of treatment plants for camps under wartime conditions was based on criteria obtained from camp sewage plants during the First World War in 1917 and 1918 (5384).

Problems of population expansion in specified locations were related, in 1942, due to the establishment of military camps such as that at Neosho, Missouri, which required that a new treatment plant be constructed which consisted of a grit chamber, a comminutor, sedimentation tanks, percolating filter, and humus tanks (4056). Sullivan and Wiley (4267) reported on the activities in southeastern United States dealing with efforts to combat pollution from military installations, and the severity of the problem prompted the issuance by the U. S. Public Health Service of a pamphlet entitled, "Notes on Basic Design Data for Emergency Water and Sewage Treatment Plants in Areas Affected by National Defense Program." Greeley (1561) stressed that the design of treatment plants handling military installation or related wastes in 1942 should provide sufficient treatment to prevent nuisance and to protect health, but that complete treatment in war time was unnecessary and expensive and some pollution was allowable.

Manning (2858) was concerned that data on 206 sewage treatment plants built during World War II at military installations and related activities which were analyzed should be applied to future design situations. The sub-committee on sewage treatment of the Committee of Sanitary Engineering, National Research Council (5590), presented data on the operation of several hundred waste treatment plants constructed at military installations in the United States. A critical study of the design and operation was conducted on these facilities. Results on characteristics of military sewage, experience with various unit operations and processes, and data representative of these treatment plant operations were described. Mohlman (3053) discussed the reports by the Commissioners of the Upper Mississippi River Basin and the National Research Council on the results of high-rate percolating filter operation. Little nitrification occurred on high-rate filters loaded with more than 2,000 lb BOD/acre/day (46 lb of BOD/

Preceding page blank

1,000 ft^3/day). Although high-rate filters were satisfactory for treating sewage from military installations, this did not mean that they were necessarily suitable for permanent use at municipal installations. Greeley (1567) reported in 1948 on the extensive experience gained on the use of high-rate trickling filters at 90 military installations and discussed design relationships with regard to performance and flexible operation.

Military procedures for waste treatment in other countries were also reported. Early British procedures, according to Balfour (157), considered each military waste plant individually and the degree of treatment depended on local conditions. Hodgson (1970) summarized Australian experience on waste treatment from military installations, and trickling filter applications were popular. French military installations (5155) generally follow separate sewage systems and when treatment was provided it was by screening, sedimentation, biological filtration with separate sludge digestion. A trickling filter which was used to treat waste waters from a National Guard Camp was the subject of a study in Japan (2246) dealing with the ecology of the trickling filter.

The unique characteristics of military installation waste waters were outlined by Hansen (1718) as being entirely domestic and free from industrial waste and contained less water and more grease. Other characteristics were the sewage flows experienced and loading rates applied. Military installations prefer higher operating costs to high installation costs. Waste water characteristics from the U. S. Army Ordnance Depot, which included waste from the vehicle repair shops, had appreciable amounts of free and emulsified oils, large quantities of suspended and dissolved solids, a pH of 7.5 to more than 10, temperatures from 50°F to 90°F, and a BOD as high as 180 mg/l (4191). Daigh (855) described the characteristics of waste from an Air Force installation which contained free and emulsified oil, chromium salts, solvents, grease, acids, alkalies, phenols, cyanides and heavy metals. A waste treatment plant built for the Pentagon in 1942 was designed to handle 1.2 mgd for a population of 40,000 which was treated at a rate of 3.2 mgd for 9 hours each day, with the sewage estimated to have a BOD of 400 mg/l and 570 mg/l suspended solids.

Thompson et al. (4379) reported that the average flow of sewage from U. S. Air Force installations was estimated at 100 gallons/capita/day for resident personnel and 30 gallons/capita/day for nonresident personnel, and the most common method of treatment was by biological filtration. The characteristics of military installation waste water were estimated by Reinke and Pratt (3554) to have an average flow of 70 gallons/capita/day with a maximum flow of three times this rate, a BOD of 0.17 lb/capita/day, suspended solids of

0.27 lb/capita/day and grease content of 0.088 lb/capita/day. During World War II, unique situations were developed at camps that were established under National Defense projects (5384) which had from 1,500 to 66,000 people and the average flow was estimated at 70 gallons/capita/day, most of which was discharged during 16 hours. The flow of waste waters from air training schools in Canada was estimated to be 60 gallons/capita/day; the original figure was modified to 100 gallons/capita/day due to an increase in consumption of water (2931).

Hospital waste water characteristics were described by Megay (2953) to have a flow greater than the amount per capita for ordinary domestic sewage (in Germany) and to be generally more dilute, higher in temperature, and contained more putrefiable organic matter. Institutional plants were reported (2772, 2948) to handle 30 gallons/capita/day (2772) up to a maximum of 10,000 gallons/140 persons/day (2948), in which treatment was provided by primary sedimentation, Imhoff tanks, sprinkling filters, secondary settling basins, and sand filters. An allowance of 350 liters (92.5 gal.)/head/day was recommended by Fontaine (1306) when designing treatment plants for hospitals due to the bacterial contamination and divergent nature of the waste, and the cost of treatment could be reduced by use of a separate sewer system for the hospital. The waste treatment works for Marcy State Hospital, New York, which were designed to treat sewage from a population of 1,000 at an average flow of 100 gallons/capita/day, was found (3805) to be overloaded, as many have been (1053), and a new plant was built to handle 1 mgd. These overloaded conditions resulted from underestimating the sewage flow per person. Typically, hospital water consumption, in 1911, was assumed at 26 gallons/capita/day and the primary sprinkling filter was dosed at the rate of 0.54 mgad (12.5 gal./ft^2/day) (2851). In 1933, Arthur (95) recommended a design of 70 gallons/minute or 100 gallons/capita/day for boarding schools. The new plant at Marcy State Hospital was designed at 200 gal./capita/day (3805).

Sewage treatment facilities at the Rockland State Hospital in Orangeburg, New York, were designed for a population of 6,000 and a sewage flow of 200 gallons/capita/day, and consisted of Imhoff tanks, bar screens, dosing tanks, trickling filters, secondary settling tanks, glass covered sludge beds, pumping plant, and chlorination equipment (2894). The effluent flow from the Danville State Hospital exceeded 233 gallons/capita/day (5126).

Waste treatment at a state school in Pennsylvania was reported by Grace (1529) to be accomplished by screening, septic tank, trickling filters, chlorination, humus tanks, and other appurtenances. Tschonhens (4471) described the equipment designed for the waste waters from a tuberculosis sanatorium handling 1,000 patients and a staff of 500. The plant includes a mechanized laundry disposal plant, biological filtration plant, algal reduction tank for final clarification, and an infiltration basin for underground disposal of the effluent. The New York State Department of Health (5655) was typical of concerned agencies involved in improving state institutions by installing new equipment such as rotating distributors on trickling filters and enclosing the waste treatment plants.

PRETREATMENT REQUIRED

Due to the natural biodegradable characteristics of the wastes generated by institutional and military installations, a great deal of pretreatment was not warranted. The usual techniques of clarification and some prechlorination were common. However, the photographic laboratory wastes at Norton Air Force Base were given pretreatment (1882) prior to discharge to municipal sewers for subsequent treatment on standard rate percolating filters or activated sludge, but more concentrated wastes were trucked to an ocean outfall disposal site. Pretreatment in the form of a 3.5-hour aerator in an institutional plant was reported by Redenour (3524) to produce a partial reduction in the BOD and a flocculation of part of the colloidal material. The net effect was the reduction of the required area of the sprinkling filter.

Wastes from the airfield at Pendleton, Oregon, were treated (5386) by a high capacity filter with provisions for chlorination prior to and after biological filtration. Daigh (855) combined Air Force metal solution wastes with sanitary sewage which were treated by biological filtration with certain of the effluent streams receiving pretreatment to condition them for biological treatment in the form of chemical addition, ion exchange, and pressure sand filtration (855). A high degree of treatment was accomplished (4191) using combined chemical and biological techniques on ordnance repair shop wastes plus post-treatment.

EFFICIENCY OF TRICKLING FILTER APPLICATION

A summary of operating results from biofiltration plants handling military wastes noted (5388) that the average consumption of water was 97 gallons/capita/day. The average flow of sewage including laundry waste was 104 gallons/capita/day. The influent waste had 193 to 340 mg/l BOD and was reduced to 9 to 43 mg/l BOD, depending on the operation of the individual installation. Hardenbergh (1729) summarized data on military installations and emphasized that 70% removal efficiencies on high-rate filters was experienced and two-stage filtration systems loaded at 8500 lb BOD/ac-f/day (195.5 lb BOD/1,000 ft^3/day) produced effluents of 66 and 53 mg/l BOD. Waste treatment facilities for military installations were required (5108) to operate for population fluctuations between 3,500 and 35,000 people. The best operating results on five army Biofilter plants were obtained (5388) from a plant comprised of comminutor, grease trap, primary clarifier, Biofilter, humus tank, and separate sludge digestion. In 1942, Fischer (1286) stated that 150 biofiltration plants were in operation or under construction in the United States, with 62% being at military installations. It was observed that 1.21 to 5.01 lb BOD were removed per cubic yard of filter medium (44.6 to 185 lb of BOD/1,000 ft^3) and power requirements (pounds of BOD removed per kilowatt hour) compared to activated-sludge systems were slightly higher. Conventional treatment employing Biofilters was described (5108) using a flow estimated at 85 gallons/capita/day with a maximum of 210 gallons/capita/day; the expected BOD removal produced an effluent containing 30 mg/l BOD and 35 mg/l suspended solids. Nelson (3159) reported on the experience of a biofiltration plant treating military waste over a period of 8 months which gave a total BOD reduction of 60 to 95%, depending on the stages of treatment employed. The efficiency of the waste treatment plants at the military installations was reported by Kessler and Norgaard (2460) to provide 85% BOD reduction by biofiltration, 60 to 83% BOD reduction in Aero-filters, and 80 to 90% BOD reduction in two Biofilters. A mechanical-biological system, which produced a 70% removal, was proposed by Wegenstein (4658) to be used for a 500-person military camp.

White (4705) reported on the overload conditions in Spartanburg, South Carolina, due to the construction of a military installation which required that a larger waste treatment plant be built. The new Aero-filter installed to increase the capacity of the sewage plant produced 90% reduction in BOD and 92% reduction in suspended solids. Another reconstruction due to overload was the Neosho plant, where a reduction of 87.5% BOD was obtained by the expanded plant (4056). Ellsworth (1162) stated that waste treatment plants composed of high-rate trickling filters serving 30,000 to 40,000 troops provided removal of suspended solids and BOD of from 70 to 90% during the winter and summer months, respectively. Rowntree (3707) used biofiltration at New Zealand military installations and loads of 2.2 $lb/yd^3/day$ (81 lb of BOD/1,000 ft^3/day) produced efficient treatment, reducing suspended solids an average of 98% and BOD 93%.

Schultz (3909) reported that effluent from a tuberculosis sanitorium treated by artifically ventilated percolating filters was 12 mg/l. Garbage grinding affected the waste water stream by increasing the BOD 200 to 290% above normal, and short periods of flow exceeded the daily average by 270% at a state school in Illinois (2503). The increased loading, however, did not appear to have any adverse effect on the percolating filters which still removed 90% of the BOD and suspended solids. A BOD of less than 20 mg/l was produced in a two-stage filtration sewage plant at the State Hospital at

Anna, Illinois, which was originally a standard rate percolating filter plant converted to high-rate operation (3627).

COMPARISON TO OTHER METHODS OF TREATMENT

Reid (3544) used biological filtration and other methods of treatment to handle aircraft cleaning wastes at a military installation. Later, efforts (3541) were made to combine the merits of Biofilters and Aero-filters to treat sewage at a Canadian Air Force installation, and forced ventilation could be applied when necessary to the filter. An evaluation of knowledge and experience was made in 1947 by Dreier (1029) who noted that the U. S. Army basis of design of 600 lb BOD/ac-f/day (13.8 lb of BOD/1,000 ft^3/day) was not excessive when other requirements for treatment were respected. Dreier also suggested that considerable experience indicated no danger in applying intermediate loadings between 600 lb BOD/ac-f/day (13.8 lb BOD/1,000 ft^3/day) of standard filters and 3,000 lbs BOD/ac-f/day (69 lb BOD/1,000 ft^3/day) on high-rate filters, particularly if recirculation was provided. Gradual improvement in efficiency with high-rate filters,at military installations in New England due to operational changes in the primary tank allowed loads at 7,000 to 9,000 lb BOD/ac-f/day (161 to 207 lb BOD/1,000 ft^3/day) with acceptable effluents. Brown (493) noted the use of high-rate percolating filters with humus recirculation and final effluent recirculation for the treatment of military installation waste in South Carolina, where dosages of 35 mgad (805 gal./ft^2/day) and loadings of 3.6 lb BOD/yd^3/day (126 lb BOD/1,000 ft^3/day) were adequately treated at this installation. Other systems were used (5590) with some success, but required skilled operation and additional capital expenditure.

Stowell (4239) reported on several methods of sewage treatment at mental hospitals, prisons, parks, and installations where percolating filters treated saline sewage. Berry (290), while questioning the blind adoption of the activated-sludge process, observed that installations such as hospitals possess a sewage flow which is too variable in quantity and composition, and personnel are not sufficiently skilled to give satisfactory results from activated-sludge operation. Typical of problem conditions was one noted by Fowler (1320), who related the experiences of C. C. James at a leper colony near Bombay. Experiments were made with septic tanks and various types of filters, including contact beds and trickling filters, with which very good results were obtained. Trickling filters have been long preferred because of their simple operation and less sensitivity to variations in quality and quantity of sewage (1306). An economic alternative was a portable waste treatment plant (5113) which contained a wood block media biological filter which could handle sewage from 400 persons at the rate of 12 gallons/capita/day with a BOD of 200 mg/l in the effluent. This system was used to handle waste treatment problems at new installations, such as schools, pending construction of permanent facilities.

POST-TREATMENT AND EFFLUENT QUALITY

Franks and Obma (1342) discussed in general the procedures and methods of treatment used at United States military installations which included Imhoff tanks, activated-sludge process, Hays Process, high-rate and standard rate percolating filters, and they observed that recirculation of filter effluents improved the performance of these plants. Sludge and oil from all repair shop processes on an Army base (4191) were stored in lagoons, and other treatment processes, including flotation, were considered. However, very little attention was paid to post-treatment devices, other than clarification and, if required, disinfection.

Megay (2953) strongly recommended that infectious sewage from hospitals be disinfected in addition to normal treatment, or be so diluted that the content of pathogenic bacteria was not greater than that occurring in domestic sewage. Many examples, such as Langlois (2619) or Bergsman and Vahlne (279), demonstrated that post-treatment chlorination of biological filtration effluent from a tuberculosis hospital required a contact period of 30 minutes and a concentration of 15 mg/l chlorine, under normal operating conditions, but under overloaded conditions 25 mg/l chlorine were necessary. However, Dixon (982) stated that calcium hypochlorite in the amount of 2-3 ppm of available chlorine was used to sterilize biological filtration effluents from a Pennsylvania hospital.

Bertelmann (300) reported that the sewage from a skin disease hospital was used for subsoil irrigation after biological filtration with no particular problems. A one mgd sewage disposal plant employing the biofiltration process satisfactorily treated waste from a state hospital and the effluent was used (2303) for irrigation. Pönninger (3419) described the waste water characteristics from three sanatoria and noted that lightly loaded percolating filters at least 4 meters (4.4 yards) deep were operated with sewage diluted 1:1, followed by sedimentation tanks and chlorine contact tanks with detention times of 1 to 2 hours.

SPECIAL OPERATIONAL PROBLEMS

A general review of military installation waste treatment plants was reported by Pedersen (3330) for installations in the 9th Service Command and problems, such as overloaded conditions and ponding of small trickling filter medium as well as unskilled operators, were observed. Concern was expressed by Owen in 1910 over the construction and operation of waste treatment plants to handle military waste for the control of disease, especially typhoid and other pathogenic organisms (3261).

Problems with military waste treatment were reported by Shepherd (3989) when a profuse growth of sulfur bacterium developed on Biofilters,and a combination of flooding and chlorination corrected the problem. Kessler and Norgaard (2460) remarked that problems with disintegration of rock and trickling filters had occurred during the operation of military installation waste treatment plants. Smith (4059) in 1915 reported on a problem which was of importance (but of doubtful significance today) at military installations, to handle waste from an army corps of 42,000 men with 10,000 horses which required extended sedimentation and trickling filter treatment. The effect of the construction of base housing at Chase Field was to overload (4653) the existing waste treatment facility. The design and construction of an additional plant rather than expand the existing one was undertaken, based on local conditions requiring a high quality effluent discharge.

Hood (2007) reported on efforts to automate military installation waste treatment by the use of oxidation-reduction potential to simplify the degree of skill required for operation. Problems which developed from underloaded waste treatment plants due to transfer of personnel at military installations included sedimentation tanks being too large, high rates of recirculation required for biological filtration, and septic conditions in influent sewage (2577). Manning concluded (2858) that standardized designs may have been justified under wartime conditions,but that they served little or no purpose under normal conditions.

Problems in the design and operation of biological trickling filters at a tuberculosis hospital were reported by Brossman (485), who indicated that the filter took six to seven weeks to mature and was infected with Psychoda. Problems in estimating the volume and characteristics of waste flows were reported by Schulz (3912) for design of hospitals and sanatoria. The peak flow was recommended to be estimated as 1/5 instead of 1/10 the average daily flow. The treatment of waste from a tuberculosis sanatorium for which it was not possible to discharge to a municipal sewer nor an available stream required extensive treatment involving both chlorination and dechlorination (3794). Antibiotics, disinfectants and other materials were discussed (2953) relative to their interference on biological treatment processes,and antibiotics were cited particularly for their inherent ability to form scum. Pratt (3455) reported a typical problem in maintenance which occurred at institutional waste treatment plants where, after excellent results were obtained the first year of operation, 18 months later the settling tanks decreased in capacity and the filters clogged because of neglect. To alleviate the inherent problem of institutional waste treatment by lack of maintenance and operation, hospital waste treatment facilities were being designed and constructed to operate automatically (5469).

Critique

The literature reflected a high incidence of use of biological filtration for the control of pollution from institutional and military facilities. These wastes, generally, were similar in character because of the absence of much of the trade wastes commonly found in a city sewer system. The investigators indicated concern and had some difficulty in establishing design flows for the facilities. Many design criteria were evaluated after several years and some agreement was shown.

By discussing military wastes in a separate section, the literature was more clearly examined. It was observed that there were definite indications during and after World War II that responsible individuals were, in essence, actually recommending limited pollution. This criticism of distinguished engineers such as Greeley is made in light of the circumstances of the times in which this nation was under the economic pressure of war. At that time, in the '40's, it was practical, expedient, and evidently safe to build waste treatment facilities with limited capability. However, for future purposes, the results of these endeavors should be noted. Many trickling filter waste treatment plants were built in which the media deteriorated or other parts of the waste treatment plant failed shortly after or during the war period. In several instances, the plants were designed so that further expansion was difficult if not impossible. Some reports indicated that biological filtration would have been phased out altogether if it were not for the remaining plants left over from abandoned military facilities.

The U. S. Public Health Service had issued information dealing with procedures and design of plants which could be installed or constructed to partially abate pollution. The military operations have favored higher operational costs and lower capital investment due to the temporary nature of the facilities built. It is hoped that the experience of the past and the total economic implications of a military facility are recognized so that if the installation is abandoned the community remaining would still have adequate, well-designed, expandable waste treatment facilities.

Institutional waste has, it would appear, been relegated to disposal by rural methods. Much concern dealing with pathogenic transfer from hospital-type installations was expressed in the literature along with workable solutions. Difficulty in defining the per capita flow at the various institutions over the years reviewed does not indicate incompetence of the investigators, but changing water use habits of the institutions. There is literature evidence that institutional and military waste treatment facilities are ideal applications for semi- or fully automatic waste treatment plants. The desire for automated waste treatment plants has been expressed in several areas. With the Government emphasizing that the waste waters from its various agencies be treated properly to conform with the issued regulations, research and development to design and evaluate an economical and reliable automated plant would be profitable.

SECTION XXIII

LAUNDRY AND CLEANING WASTES

Waste water generated from laundry and cleaning activities can possess an extremely variable character. These wastes can be organic, inorganic, acid, alkaline, or even radioactive. Obviously, no one single method of waste treatment can treat all of these wastes satisfactorily, although trickling filters have been accepted widely in this application.

Because of the variations in flow, strength, and characteristics of laundry waste waters, chemical and biological processes at small sewage works may be seriously affected. Gehm (1440) maintained that sewage works with a total flow of more than 5 mgd usually experience little difficulty treating laundry waste waters. Boyer (433) found laundry waste waters to be alkaline, turbid, and to contain large quantities of soap, soda ash, grease, dirt, dyes, and cloth scourings. According to Spade (4129), high-rate trickling filters were most suitable for efficiently lowering the concentrations of suspended solids and BOD from this type of waste. In a survey of four laundries in Dayton, Ohio, Hommon (1991) found that BOD concentrations ranged from 91 to 333 mg/l, while the suspended solids averaged 113 to 473 mg/l.

McCarthy (2896, 2897) did extensive work at the Lawrence Experimental Station on laundry wastes with a pH of 11, caustic alkalinity as high as 1,000 mg/l, and a grease content of 267 mg/l. The laundry waste was satisfactorily treated on a rock trickling filter, 8 feet deep, at an application rate of 5 mgad (115 gal./ft^2/day). Jenks (2303) used a 2.5 mgad (57.7 gal./ft^2/day) feed rate, but recirculated additional settled sewage through the filter. Foth (1316) reported on a 10.8 mgad (248 gal./ft^2/day) filter feed rate of combined sewage and laundry waste plus dairy waste water. Liberty, New York, which experiences a large summertime influx of tourists, operated two trickling filters in series which handled large volumes of laundry waste (5381). The BOD loading to the filters was 3.17 lb/yd^3 of stone (117 lb BOD/1,000 ft^3/day) and both filters utilized a 2:1 recirculation ratio (5381).

Trickling filter treatment of laundry wastewater effluent from the cleaning of radioactive contaminated clothing was investigated by Newell et al. (3176, 3177). Beside containing soap, detergents, citric acid and lint, this waste contained alpha activity due to plutonium averaging 1,000 counts/min/l. Dobbins (984) showed that the amount of activity removed by two-stage filtration is about the same as that removed by single filtration when the total volume of filter medium is the same.

Waste water from laundries in which clothing was contaminated with explosives was treated (4730) by trickling filters after mixing with domestic sewage in a ratio of at least 4 volumes of sewage to 1 volume of laundry waste. Reid and Janson (3544) and Reid and Libby (3545) confirmed that waste water from cleaning operations involving aircraft maintenance was adequately treated with trickling filters. The most difficult portion of the waste emanates from the decarbonization of aircraft engine parts. Troublesome contaminants include cresylic acid, a mixture of ortho-, meta-, and paracresols.

PRETREATMENT REQUIRED

Pretreatment of cleaning wastes in certain instances has enhanced the efficiency of trickling filter operations. With respect to laundry waste water, Enslow (1178) advocated the precipitation of alkaline laundry wastes by the addition of acid prior to further treatment. Milk of lime added to a sewage-laundry waste mixture was found by Drummond (1035) to improve operation and reduce odors. At another plant, lime and chlorinated copperas as coagulants were added to the waste water prior to settling and filtration (5214). In the treatment of radioactive laundry waste water, Wiederhold (4715) recommended adding ammonium nitrate as a nutrient prior to biological filtration. In his studies, Newell (3177) found it necessary to add phosphate in addition to ammonia. Wilkinson (4730) recommended that separate settling of laundry and domestic wastes be employed before mixing of the two together and loaded the experimental trickling filter at a rate of 63 gal./yd^3/day.

Waste water from aircraft cleaning in tank washing operations invariably required (3544) pretreatment before biological filtration. The same authors applied batch pretreatment techniques, such as skimming to remove oil, neutralization with lime, and the addition of diammonium phosphate, on engine cleaning wastes to break an emulsion of cresol-type compounds. Reid (3545) noted that waste phosphoric and nitric acids would supply necessary nutrients to phenolic waste water which was in the alkaline state. Gutzeit and Enyart (1631, 1632, 1633) treated waste waters from the cleaning of tank cars and described a pretreatment system of adsorption on coal, coagulation with ferrous sulfate and lime, settling, storage in a lagoon for five days mixed with domestic sewage, followed by a trickling filter. Safronova and Yaroshevskaya (3810) cautioned that filters handling laundry waste mixed with sewage must be gradually matured. Hartmann (1776) stressed that treatment of "new" detergents in 1967 by biological systems which were properly acclimatized was still difficult due to the poor nutrient quality of the detergents. Corder (789) reported on the use of Bionetic at an airport installation to reduce the formation of grease and scum in the trickling filter plant.

EFFICIENCY OF TRICKLING FILTER APPLICATION

Trickling filters have been reasonably efficient in removing contaminants from cleaning waste waters. Studies of laundry waste treatment at military installations revealed BOD and suspended solids reductions in the range of 81 to 89% when double filtration was employed (3012, 5388). Newberry et al. (3174) blended raw waste with sewage and used two different recirculation ratios on one filter. They obtained efficiences of 91% BOD and 89% suspended solids removals at a 2:1 recirculation rate, and 88% BOD and 91% suspended solids removal at a 1:1 rate. Without any chemical pretreatment, Boyer (433) tested a single stage limestone filter with application rates of 2, 1, and 0.5 mgad (46, 23 and 11.5 gal./ft^2/day) of raw waste. The BOD removals for each rate were 62%, 76%, and 85%, respectively. Crawley and Brouillette (815) studied the performance of laundry wastes on plastic media and obtained removals of 73% of BOD, 40% of alkylbenzene-sulfonate, and 72% of the suspended solids.

Dobbins (984) claimed that 90% of mixed fission products from radioactive laundry waste water was removed when the waste waters contained detergents plus citric and nitric acids. Using a similar waste, Newell et al. (3177) found that biological treatment on a single stage filter was effective only when settled effluent was recirculated at a ratio of more than 8:1. Operation of two filters in series with recirculation ratio of 6:1 or more also produced satisfactory results with BOD removals of 90% or more. Cleaning wastes from aircraft maintenance activities were investigated by Reid and Janson (3544) and it was found necessary to dilute the waste with sanitary sewage before reductions of 80% phenol and 75% BOD were realized with biological filtration. Phenol present in waste waters from tank car cleaning operations was reduced from initially 208 to 864 mg/l to finally less than 1 mg/l when trickling filters were used in conjunction with adsorption on coal and chemical coagulation (1631, 1632).

COMPARISON TO OTHER METHODS OF TREATMENT

The trickling filter process does not have a monopoly in the treatment of cleaning waste waters (4876). Moore (3080) noted that laundry wastes were treated on trickling filters or by chemical coagulation. Boyer (433) outlined a coagulation process involving pH adjustment (6.4 to 6.6) with sulfuric acid, followed either by 240 mg/l of ferric sulfate, 160 mg/l ferric chloride, or 200 mg/l aluminum phosphate, obtaining BOD reductions of 85 to 90%. Ferrous sulfate and sodium aluminate caused no precipitation, but alum dosed at 23 grains per gallon of waste formed a rapid settling floc, according to McCarthy (2896). Gehm (1440) stated that the addition of sulfuric acid with alum or ferric sulfate lowered the amount of these chemicals needed for coagulation. Carbon dioxide proved to be less effective than sulfuric acid when examined for decreasing the amount of ferric chloride required for coagulation. The same researcher found that 500 mg/l of magnesium sulfate coupled with 800 mg/l lime achieved high BOD removals.

Trickling filters were judged preferable to chemical precipitation since they required little operating skill, cost of chemicals was avoided, they were more adaptable to fluctuations and could be used for partial treatment. Spade (4129) found that the high-rate trickling filter operation efficiently reduced suspended solids and BOD from laundry wastes. He cited comparative costs and operating problems of sand clogging and odor nuisance for open sand filters. Gehm (1440) maintained that sewage containing up to 20% laundry waste could be treated by the activated-sludge process with normal periods of aeration. Snook (4091) observed that it was necessary to reduce the flow of laundry waste to an aeration tank to avoid bulking. Laundry waste applied to plastic media trickling filters compared favorably with the activated-sludge process (2944) as well as with package treatment plants (643).

Wiederhold (4715) and Pazdernik (3317) reviewed the treatment of these wastes by both the activated-sludge process and biological filtration. Newell et al. (3177) compared the coagulation of radioactive laundry waste by ferric chloride and lime, followed by biological filtration and then slow sand filtration. Calcium chloride, sodium hydroxide, activated silica, and iron chloride were used for radioactive waste prior to an activated-sludge process but excessive foaming was observed by Ruf (3776) and by Newell et al. (3177). Chemical treatment produced 25 to 30 times more sludge than that produced by biological filtration. Dobbins (984) noted that the radioactivity removed by two-stage filtration was about the same as that removed by single-stage filtration when the total volume of filter medium was the same.

The treatment of aircraft cleaning waste waters high in phenol content was compared by Reid et al. (3545, 3547) on rotating drums, by biological filtration, and by the activated-sludge process. Wastes high in phenol content were best handled on rotating drums, although trickling filters were able to handle concentrations below 100 mg/l. The activated-sludge process was capable of treating phenol up to 500 mg/l with a BOD of 1,000 mg/l. When the waste contained cresylic acid and various cresols, an Aero-accelator was able to achieve substantial BOD and phenol reductions if suitable pretreatment was employed (2355, 3544). One airport (5258) did report trouble with the activated-sludge process when oils, phenols, and metal plating wastes were encountered, and a high-rate biological filter with recirculation was constructed as the substitute treatment process.

POST-TREATMENT AND EFFLUENT QUALITY

Additional treatment on cleaning wastes following biological filtration has been employed in some instances. In most cases, sand filtration was the most popular choice of post-treatment. At Liberty, New York, settled two-stage filter effluent from a combined domestic sewage-laundry waste mixture (5381) was fed to a magnetite filter at a filtration rate of 1.5 gal./ft^2/min (2160 gal./ft^2/day). In Covina, California, ferric chloride was mixed with effluent from a trickling filter humus tank and passed through a rapid sand filter (2536). The filtrate was then chlorinated and fed to underground percolating wells. Gutzeit (1633) mentioned that tank car cleaning effluent from a filter was disinfected with chlorine dioxide before discharge. With regard to radioactive waste water, Wiederhold (4715) recommended either two-stage trickling filter operation or final coagulation of the effluent to remove residual radioactivity. Newell et al. (3177) found rapid sand filters satisfactory for removing suspended matter from a radioactive trickling filter effluent.

SPECIAL OPERATIONAL PROBLEMS

The treatment of cleaning wastes has caused some abnormal operating problems. Spiess (4146) reported that a sewage-laundry waste mixture encouraged the abnormal growth of filter flies at one particular plant. The most effective fly control method employed the application of trichlorobenzene to the filter which was flooded and allowed to stand overnight. In the treatment of radioactive laundry wastes, difficulty in chemical coagulation prior to filtration was encountered, probably due to the presence of complexing agents (3177). Gehm (1440) observed that the irregular flow pattern of laundry waste was felt most on Mondays and Tuesdays. The grease and suspended solids levels on these two days were 14% higher than the Monday through Friday average, while the BOD was 12% greater.

Critique

Cleaning wastes were shown to be adequately treated by biological filtration after proper pretreatment. It should be noted that ABS type detergent wastes were never treated adequately, but the impurities carried in the waste streams were handled effectively. With the removal of hard detergents from the general market, additional BOD was loaded to the system, but total removal was greater. Chemical pretreatment was shown to be required for cleaning wastes to remove high suspended solids and toxic elements. The trickling filter system was shown to be of value here, as in other areas, where heavy metals or toxicants were discharged. Also, the intermittent flow of laundry wastes placed the recirculating trickling filter process in a desirable position. Sufficient experience was reported in the literature to properly design and operate biological trickling filter plants to handle laundry and cleaning wastes.

SECTION XXIV

MEAT AND POULTRY WASTES

Meat packing wastes were listed (308) as having been successfully treated on biological trickling filters and, therefore, the quantity of available literature is large. A general discussion of the literature and practice of the disposal of meat packing wastes was published in 1966 by Steffen (4203), which outlined several alternative methods of treatment, as well as the waste water characteristics, and the advantages of producing salable by-products from the waste treatment processes.

The growth of the meat packing industry in the United States affected the waste water characteristics, and Hill (1949) stated that the volume of waste water per 1,000 pounds of animals killed usually ranged between 835 and 4,160 gallons. The seasonal variation in the waste characteristics indicated that 20% above the average were killed in the winter, while 10% below the average were killed in the summer. The BOD and the suspended solids per 1,000 pounds of animals killed varied from 5.2 to 18.9 pounds and from 2.9 to 22.0 pounds, respectively. During the weekdays, according to Cropsey (826), more than 90% of the sewage flow to the South St. Paul sewage plant consisted of waste waters from the meat packing industry. On slaughtering days, the sewage characteristics were 28,000 mg/l total solids, 781 mg/l suspended solids, a BOD of 1,009 mg/l, and by rather conventional treatment the BOD was reduced to 236.8 mg/l, suspended solids to 51 mg/l, and the total solids to 1,751 mg/l. A paper published in Waste Engineering (5619) in 1956 stated that the most satisfactory method for treating meat waste was in admixture with domestic sewage.

Usual treatment processes which have been used (5619) included fine screening, sedimentation, chemical precipitation, biological filtration and the activated-sludge treatment as well as various chemical precipitants. Nichols and Mackin (3184) reviewed work of British investigators handling meat packing wastes and listed, typically, that a treatment plant included a grit chamber, grease extractor, primary settling tank, a sludge digestion chamber, a secondary settling tank, a mixing tank where domestic sewage was added, a third settling tank, a cascade aerator, and an intermittent sprinkling filter followed by humus tank. Dual treatment by trickling filter-activated sludge systems, as well as mechanically backwashed trickling filters, was reported by Hill (1949). Steffens (4204) described waste treatment from small abattoirs in which the waste was characterized as resembling domestic sewage, but was much stronger and required grease traps, screens, and a settling tank with a capacity for one day's flow. If the effluent was to be discharged to a stream, then trickling filter treatment was recommended.

Another plant was described by Howson (2071) as containing fine screens, grit chamber, grease filtration, flocculation, primary sedimentation, primary trickling filters equipped with air and wash-water operated at 6 mgad (138 gal./ft^2/day), intermediate clarifiers, with one hour detention time, and either two- or three-stage biofiltration, which operated in parallel or series as required. The filters were normally operated in parallel at the rate of 1.4 mgad (32.2 gal./ft^2/day).

Meat packing wastes have been problems in several countries, e.g., New Zealand (3705), and the data were similar with those of typical plants in the United States. Meat packing waste water characteristics were described by Aikins (25) as quite similar to domestic sewage, and combined municipal-trade waste waters were satisfactorily treated by percolating filters or by activated-sludge plants. According to Just (2359), once the fat and blood were removed, the wastewater characteristics were quite similar to those of domestic sewage, and admixtures of up to 50% could be treated satisfactorily by biological filtration. Chief characteristics of waste waters from packing houses are the high temperature, and the high content of sodium chloride, fats, organic nitrogen, nitrates, and total solids (2708). Most of the effluent from a poultry packing station was discharged during the short periods of wash-down operations (5575). Rowntree (3705) suggested conventional treatment of waste waters of meat packing and slaughter houses by biological filtration or activated sludge, while Heukelekian et al. (1922) used high-rate filtration.

Russell and Axon (3788) described a municipal treatment plant in Tennessee which utilizes trickling filters as a roughing device for domestic sewage and meat packing wastes. The operation of the Cedar Rapids, Iowa, waste treatment facility, which was receiving intermittent discharge of a packing house waste, was detailed in a series of articles by McIntyre (2916, 2917, 2918). Melzer (2966) studied the applicability of treatment of meat packing waste with an average BOD of 2,140 mg/l over a tower trickling filter filled with blast furnace slag which had provision for intermediate layers of air. Deyl (943) tested Biofilters 5 and 6 m high (16.4 and 19.7 ft) to treat slaughter house wastes. The optimum loadings were 2,000 g BOD/m^3/day (125 lb BOD/1,000 ft^3/day) with recirculation, 8,000 g (511 lb BOD/1,000 ft^3/day) for continuous operation without recirculation, and 5,000 g (311 lb BOD/1,000 ft^3/day) for shift operations without recirculation.

Heukelekian (1922) characterized the waste waters from four poultry processing plants where the flow of waste water per 1,000 chickens varied from 2,620 to 7,000 gallons. The highest figure was due to the large volume of water used during killing and plucking, but the BOD and suspended solids resulted primarily from wash water of batteries or coops. Wash water figures at 5,460 gallons per 1,000 turkeys and 2,200 gallons per 1,000 chickens with BOD contributions of 80 pounds per 1,000 turkeys, and 31 pounds per 1,000 chickens were also recorded (5575). An average suspended solids load was 51 pounds per 1,000 turkeys and 11 pounds per 1,000 chickens. Data collected by Kountz (2557) showed that the BOD load was 25 pounds per 1,000 chickens. For plants using the "flow-away" system for processing feathers and offal, Bolton (397) calculated that 6,000 gallons of water per 1,000 chickens processed was reasonable if water conservation measures were taken. In a plant in which manual removal of feathers and offal was employed, the volume of waste water was 2,600 gallons per 1,000 chickens processed. When reasonably efficient blood recovery is practiced, the waste waters had a BOD of 25 pounds and contained suspended solids of 12 pounds per 1,000 chickens processed. Sharpley (3972) described a trickling filtration plant which treated domestic, milk processing, and poultry processing wastes at a rate of application of 420 gal./yd^3/day. Whiten (4714) recommended filtration through a roughing filter and a standard rate filter for a sewage plant treating predominantly wastes from the poultry processing industry.

PRETREATMENT REQUIRED

Plants utilizing trickling filters were recommended by Bolton (397) to employ preliminary aeration as a pretreatment step. He also stressed that for economic reasons, as well as for ease of treatment, it was important to provide an efficient recovery of blood, adequate screening for removal of feathers and offal, and removal of gizzard contents at the processing plant. As a pretreatment measure, Roberts (3640) observed that all poultry processing plants were required to install screens to reduce the amount of feathers and grit reaching the treatment plant.

Bryan (518) discussed pretreatment at a Wisconsin meat packing plant which treated its waste waters by biological filtration prior to discharging the effluent to the municipal sewage treatment plant, where it is further treated by activated sludge and biological filtration. Combinations of trickling filters and activated sludge were utilized (516) to treat meat packing wastes prior to discharge to the municipal wastewater treatment plant. Martin (2876) gave the requirements for construction of slaughter houses in France. Where the effluent could not be discharged into sewers or a river, the treatment included settling, either mechanical or with addition of chemicals, and trickling filters or broad irrigation. Anaerobic digestion was used by Hicks (1933) to reduce the BOD from 2,000 mg/l to 200 - 400 mg/l, which was amenable to further treatment on percolating filters or other aerobic systems.

Packing house wastes were reported by Garrison and Geppert (1417), in 1960, to receive preliminary treatment by sedimentation and grease recovery prior to discharge to municipal sewers. With regard to rendering plant waste waters, Granstrom (1533) claimed that a recirculation ratio of at least 2:1 must be maintained to dilute the waste and equalize the strength. At loadings greater than 5 pounds of BOD/yd^3/day (175 lb of BOD/1,000 ft^3/day), the mixed waste water and the recirculated effluent should be pretreated by aeration prior to filtration. Rohde (3669) added iron sulfate and lime to sewage entering the sedimentation tank and the sewage was also aerated in a preliminary section of the tank. The percolating filters were completely enclosed and aerated from the top.

Anaerobic digestion of meat packing waste waters was reported by Steffen (4201) as a pretreatment to biological filtration, followed by sedimentation and chlorination. Silvester (4027) reported, in 1962, that anaerobic digestion at 33°C was the preliminary treatment prior to biological filtration to produce a settled effluent acceptable for discharge.

Primary sedimentation was used in chicken packing plants (1922) to reduce the content of suspended solids in mixed waste waters by 80% and the BOD by 40%. Blocks of aluminoferric were placed (4068) in the waste channels prior to primary settling to improve sedimentation of effluent from poultry dressing plant since most of the impurity in the waste water was colloidal. Grit removal, aeration and coagulation with ferrous sulfate and chlorine were used in France (5046) prior to high-rate percolating filters. When a flotation unit preceded biological filtration, the addition of 20 mg/l of alum to the waste water did not affect the performance of a filter. Crist (819) reported that a plant designed to treat domestic and industrial waste including poultry processing waste waters used pretreatment with lime and chlorinated copperas to adjust the pH and to improve sedimentation for removal of 50% BOD and suspended solids.

When blood pretreatment removal techniques were employed (5575), the BOD of poultry processing wastes was reduced by 41%. It was suggested by Just (2359) in 1939 that it was economical to recover the fat and blood from the waste waters of abattoirs. Acid precipitation was used (4979) to remove as much grease and organic matter as possible prior to trickling filters in the treatment of waste waters containing a high grease content from wool scouring.

EFFICIENCY OF TRICKLING FILTER APPLICATION

Typical of the relationship of meat packing waste to a municipal population was that reported by Hansen and Hill (1716), where waste waters of a population of some 18,000 were combined with the effluent of a packing house which had an equivalent of 195,000 people. Pretreatment was heavy chlorination, followed by sedimentation which would reduce the BOD's from 2,000 to 600 - 800 mg/l, and the suspended solids from 1,900 to 200 mg/l before discharge to the sewers. They stated that 70% BOD reduction could be obtained by recirculation ratios of 3:1 through biological filters. Bragstad (439) reported that after chemical-biological treatment, the final effluent contained 9.9 mg/l suspended solids and had a BOD of 10.6 mg/l based on an influent of 2.6 mgd of domestic sewage and 1.7 mgd of meat packing waste water which contained 403.1 to 720 mg/l suspended solids and BOD's of 324.7 to 954.7, respectively. Seven years later modifications to this plant were described by Hill (1948), which involved changes in the settling tank weir system and increased the BOD removal from 40 to 55%, and suspended solids from 60 to 65 - 70%. Once the modifications were installed, 90% BOD reduction was achieved across the filters. Levine (2699) reported, in 1935, that the BOD of settled packing house waste could be reduced by 97% and the organic nitrogen content by 95% using an application rate of 7 mgad (161 gal./ft^2/day) on an aerated granite filter followed by percolating the settled effluent through a cinder or gravel filter at the rate of 3 mgad (69 gal./ft^2/day).

Overall BOD removal through the chemical-biological filtration plant treating poultry waste waters was 93% at loading rates of 1.35 lb of BOD/yd^3 of medium/day (50 lb of BOD/1,000 ft^3/day), according to Crist (819). British installations were noted to produce 90% removal. Meat packers have on occasion built and operated adequate waste treatment facilities (4837) which produced acceptable effluents. One million gallons a day of screened packing house waste were treated (4487) to 92.7% BOD removal by biological trickling filtration on a quartzite filter, 1.3 acres in area and 7 to 8 feet deep, with fixed sprays. Eldridge (1143, 1148) reported on the troublesome characteristics of a meat packing waste in Michigan. He indicated that a percolating filter plant with recirculation removed 99.2 to 96.6% BOD from a septic tank effluent and, after dilution with cooling water from the refrigeration plant, the final effluent contained 5 to 12 mg/l of BOD. Levine (2708) observed that the overall reduction of BOD by a standard filter treating packing house wastes was 400 lb/ac-f of medium (9.2 lb BOD/1,000 ft^3/day), as compared to the reduction of 1,000 lb/ac-f of medium (23 lb BOD/1,000 ft^3/day) by the primary filter of a two-stage filtration plant. Investigations (1417) on the use of plastic media filters indicated that 70% of the BOD could be removed at high rates of loading of packing house waste waters. A waste treatment plant handling meat packing wastes in North Dakota was reported by Howson (2071) to handle

700,000 gpd and reduced the BOD by 95%. After primary filtration, the BOD which had an influent of 1,000 mg/l had been reduced to 250 to 300 mg/l.

When packing house wastes at Cedar Rapids, Iowa, with a daily volume of 1.2 mg and a BOD of 2,000 mg/l, and sometimes 4,000 mg/l, were discharged to the Cedar Rapids waste treatment facility, the influent BOD was satisfactorily reduced by 40 to 50% after an elaborate sequence of clarification and filtration aided by a roughing filter (5097). A roughing filter used in Oklahoma City was reported by Cunningham (841) to reduce the BOD to 60 mg/l on an influent of combined domestic sewage and packing house waste. A pilot plant biological filter, studied by Hirlinger and Gross (1959), operated as a high-rate unit with a rate of flow of 20 mgad (460 gal./ft^2/day) and a recirculation rate of 50%, producing a reduction in BOD of 50% with BOD loadings as high as 4.97 lb/yd^3 (184 lb BOD/1,000 ft^3/day). During the nonkilling hours, when the BOD load on this filter was about 2.06 lb/yd^3 (76 lb BOD/1,000 ft^2/day), the average reduction in BOD was 61.2%.

COMPARISON TO OTHER METHODS OF TREATMENT

Steffen (4202) discussed and compared various methods of treating slaughter house waste waters including that of biological filtration. Biological filtration and the activated-sludge process have not been widely used (3436) in poultry plants because of the high capital cost and the care required in operation, but an extended aeration modification of the activated-sludge process was used at one plant. Meat processing plant waste waters were treated by the extended aeration process, which was explained by Willoughby and Patton (4739) to have certain advantages over conventional activated sludge and over two-stage biological filtration. Kountz (2556) determined that neither the activated-sludge process nor biological filtration was suitable for treating waste water from small slaughter houses because the BOD was too high for biological filtration, except with several stage operation or with high recirculation rate. However, he showed that a coal filter operating at 20 mgad (460 gal./ft^2/day) without recirculation reduced the BOD by 40%, indicating that this method could be used as a possible preliminary treatment.

Mohlmann (3041, 3054) reported, in 1928, that activated sludge was chosen for the treatment of packing house wastes in Chicago rather than trickling filters due to the equal performance and more economical installation cost. Waste waters from packing house installations in Oklahoma City were studied by Benham (272), and the advantages of two-stage percolating filters, two-stage biofiltration, and the activated-sludge process were observed, with the two-stage percolating filter method of treatment adopted. Final results of studies by Deyl (943) showed the advantages of tower percolating filters over the activated-sludge process for treating slaughter house waste waters. He concluded that there was no difference in the results achieved by batch or in continuous operation which permitted treatment on a more economical shift basis, an operating procedure not possible with the activated-sludge process. Levine et al. (2702) reported that the poor efficiency of an activated-sludge plant (54.9% removal BOD) on a packing house waste did not refer to the unsuitability of the activated-sludge process to handle meat packing wastes, but to the unusually high salt content. The percolating filters removed 1,173 to 4,343 lb of BOD/ac-ft(27 to 100 lb BOD/1,000 ft^3/day) by primary filtration, and 246 to 1,362 lb/ac-ft(5.7 to 31.6 lb BOD/1,000 ft^3/day) by secondary filtration.

Schroepfer (3904) compared the anaerobic process for treating waste waters from meat packing houses where, for removal of BOD and suspended solids of 95%, a loading of 0.2 lb of BOD/ft^3 of digestion tank per day was required. To obtain the same degree of purification by the activated-sludge process or percolating filters, loadings of only 0.02 to 0.05 lb of BOD/ft^3/day (20 to 50 lb BOD/1,000 ft^3/day) were possible. Schroepfer et al. (3905) reported the cost of treatment by anaerobic digestion when compared to biological filtration was approximately one-half to effect an equivalent degree of purification. However, the costs of operation and maintenance were slightly greater to produce a 95% BOD and 90% suspended solids removal. Syme (4281) stated that conventional treatment by biological filtration or activated sludge was not entirely satisfactory for treating waste waters from meat processing plants in New Zealand and that good results were obtained at some plants using anaerobic digestion.

High-rate filtration, which could be backwashed with air and effluent, was often used for the treatment of packing house waste in 1940, according to Fischer (1281). Quite often, small slaughter houses have required extensive treatment and it was indicated by Stiemke (4218) that treatment by biological filtration of settled waste waters with recirculation was poor. Satisfactory results were obtained on sand filtration where waste waters with a BOD of 800 mg/l with little or no settleable solids were applied at rates up to 150,000 gal./ac/day (3.45 gal./ft^2/day). Chemical coagulants, such as alum and calcium hypochlorite or chlorinated lime, produced an average reduction of BOD of 95% and a clear colorless effluent. Kountz (2557) compared the cost for percolating filters vs. spray irrigation and subsurface tile fields to be in favor of the latter, but percolating filters were made more competitive by adopting recirculation.

POST-TREATMENT AND EFFLUENT QUALITY

Rather than building an expensive post-treatment device in 1937, Jacoby (2259) used abandoned strip mines to serve as oxidation ponds and final sedimentation units. The BOD was reduced from 100 mg/l coming from the filter to below 20 mg/l. Addition of sodium nitrate, however, was required to assure a high quality effluent. Lagoons were used (3436) successfully for treatment of poultry wastes or in admixture with domestic sewage. Disposal by irrigation was satisfactory, but required a large amount of land. As a form of final treatment, the use of grassland irrigation for the trickling filter effluent was encouraged (5575).

Smith (4068) found that it was preferable to recirculate unsettled trickling filter effluent rather than final settling tank effluent to establish high quality effluent. In Gainesville, Georgia, Mower (3106) described the provisions made to apply chlorine to the recirculating effluent from trickling filters used to process meat wastes. French experience (5046) demonstrated that an effluent BOD of 10 mg/l and suspended solids of 20 mg/l could be achieved in a chemical precipitation - high-rate biological filtration plant treating slaughter house waste waters.

SPECIAL OPERATIONAL PROBLEMS

Typical operational problems that have occurred on waste treatment plants handling meat packing wastes were reported by Lovell (2764) in 1941. The surface of the trickling filters at Fort Dodge, Iowa, was continually clogged and had to be cleaned mechanically and by hosing. Operations were improved using chlorination and post-primary sedimentation. Increased sloughing, reduced clogging and improved efficiency were observed, and the overall performance of the plant was 91% reduction in BOD and 90.4% reduction in suspended solids. Shepherd (3989) had problems with the medium in the percolating filters and it was removed, screened, washed, replaced. Older percolating filters were equipped with new rotary distributors.

Ingols (2219) has found that large quantities of detergents, when mixed with chicken processing wastes, interfered with sedimentation and thus resulted in overloading of the trickling filters. Biological purification of meat packing wastes was the recommended treatment in France (665, 3393) where concentrations of organic matter in the heavily polluted water may be more than 6,000 mg/l with 20 to 30 times as many pathogenic bacteria as in domestic sewage. It was also recommended that a closed aerated percolating filter be used at least on small plants.

Banister and Cloud (164) described the expansion of an existing biological filtration plant to include a conventional activated-sludge unit to follow the trickling filter as second stage treatment. Difficulties realized during operation have been due to the presence of feathers and turkey lungs. Light perchlorination was used when excessively large quantities of blood were discharged at a Department of Agriculture Research Center (5096) and, with a combined chemical treatment - trickling filter plant, BOD reductions in excess of 90% have been achieved.

The method of charging industries to treat their waste waters encouraged them to effectively reduce the volume and strength of waste entering the treatment plant by 50 to 56% (Reaves, 3521).

Critique

The heavy coverage in the literature on biological trickling filters was indicative of the successful use and some problems which were reported during the treatment of meat packing, slaughter house, and poultry processing waste. The wastes were adequately categorized and characterized as to organic content, suspended solids, inorganic content, pH, and other operational factors. Grease was identified as a primary problem and several authors stressed that pretreatment was of importance for the removal of grease and blood prior to biological treatment using trickling filters or activated-sludge processes.

The value of salable byproducts from waste treatment and recovery of materials was recognized early by several workers and reemphasized recently. It was noted that poultry processing wastes have changed slightly over the years due to increased mechanization and that quantities of wash water required have increased, but systems have been developed to recycle wash water which reduced the pollutional effects. The removal of feathers and other parts of the poultry was important, since these materials interfere with the unit operations of waste treatment facilities.

It would appear that sufficient evidence has been provided by investigators over the years to demonstrate that the waste waters discharged from meat processing and poultry processing plants may be rendered biodegradable. Available evidence indicates that, because of the severe conditions imposed on a waste treatment plant by these wastes, pretreatment is required and techniques have therefore been developed. Most operational difficulties have been overcome with the result than an economical waste treatment facility may be operated with a minimum of trouble. It should be considered, however, that only through proper maintenance and continually modified operation will these wastes be adequately treated. If a waste treatment plant is allowed to deteriorate, such as biological trickling filters developing plugging conditions or dense fly populations, intolerable effluent will be discharged to the receiving body of water, as well as poor conditions for the local treatment plant environment.

SECTION XXV

METAL WORKING WASTES

The sources, composition and treatment of electroplating wastes were described in a comprehensive review by Pettet (3352). The safest method of disposal of plating wastes was reported to be by discharge into a public sewer, with permission from the local authorities, although pretreatment of some sort was indicated. Cyanide wastes were treated (3352) on a biological trickling filter with or without an admixture of domestic sewage, and a review of the treatment of cyanide waste waters was published by Brink and Thayer (462). Mohlman (3051) reviewed the various developments in percolating filters and activated sludge for the treatment of wastes from the metal and other industries in 1946. A critical review of the literature published in 1952 compared various methods of treatment of industrial and municipal wastes in which biological filtration was compared to activated sludge and mechanical filtration (5582). The composition of waste from U. S. Air Force installations was described by Thompson et al. (4379) as a variable flow domestic sewage which contained plating and metal wastes, plus waste waters from cleaning of engines and fuselages and painting.

PRETREATMENT REQUIRED

Most investigators found that some type of pretreatment, such as screening, pH adjustment, or sedimentation, was required for the treatment of metal wastes by biological filtration. Eldridge (1139) discussed the effects of various industrial wastes, including metal plating and acid mine drainage, on municipal waste treatment plants. Many acid metal wastes required pretreatment, such as neutralization and removal of certain metal ions, to prevent overloading or destruction of biological processes. When the proportion of industrial wastes to domestic wastes was high, pretreatment definitely was advised. Rummel (3781) treated brown coal mine wastes on a pilot plant scale using lime water, aeration, and rapid filtration. Pretreatment by flocculation of the iron was used and pH adjustments in the range of 6.8 to 7.4 were satisfactory. A rather unique method of treating plating wastes on percolating beds, which also doubled as sludge drying beds, was discussed by Rincke (3620) and involved pretreatment to oxidize cyanide and reduce chromium. Pretreatment of plating wastes, such as alkaline chlorination of cyanide, was also recommended by Kittrell (2502). Pretreatment by screening, neutralization, coagulation and sedimentation of alkaline wastes from roller bearing manufacture was also used before the secondary treatment of screening, comminution, primary sedimentation, two-stage biological filtration, and final sedimentation, as described by Geyer (1462). Stolbov suggested (4225) that certain trade wastes, such as metal and phenolic wastes, could be mixed with domestic wastes which would make them amenable to biological treatment without the use of a Biofilter. Chlorination was used for preliminary treatment and was combined with electrolysis for the recovery of metals.

EFFICIENCY OF TRICKLING FILTER APPLICATION

Working with plastic trickling filter media on a laboratory- and pilot plant-scale basis, Porter and Dutch (3437) demonstrated that consistent removals of 95% phenol and 90% cyanide were readily attainable for various coke and steel wastes. These high removals were accomplished on synthetic feed solutions of phenol and cyanide. The effect of sulfides in concentrations up to 15 mg/l was negligible. The treatment of gas plant wastes and other ferrous metal industry wastes by alternating double filtration reduced the BOD from 150 to 11 mg/l (3014). In 1928, Drury (1036) described the installation of sprinkling filters in combination with Imhoff tanks to alleviate the severe pollutional load from an automotive assembly plant. Concentrations of free cyanide as high as 150 mg/l could be removed by biological filtration; however, cyano-copper complexes were much more difficult to treat (462). A filter designed to treat waste pickle liquor, spent gas liquor, and other trade waste waters was described by Hunter and Cockburn (2100). The biota and efficiency of these filters, operated both closed and open, were compared. Koch (2533) reported successful treatment of phenolic metal wastes on biological trickling filters.

Experiments by Green et al. (1571) with domestic sewage containing a high fraction of metal finishing wastes indicated that the greatest growth occurs on Biofilter media when the biofilm was at 20°C, with BOD removal of 95%. At 30°C, performance was much the same, while at 5°C BOD removal was less than half. Satisfactory treatment of synthetic rubber wastes containing copper and chromium was obtained on high-rate aerated percolating filters, according to Munteanu et al. (3126). Hydraulic loadings were from 0.5 to 1.0 $m^3/m^2/hr$ (295 to 590 gal./ft^2/day) with BOD_5 loads of about 0.3 to 0.5 kg/m^3/day (18.9 to 31.6 lb BOD/1,000 ft^3/day). Nutrient addition in the form of domestic sewage was unnecessary, provided that sufficient phosphorus was available. The detrimental effects of copper and chromium were discussed. Foundry slag and vermiculite were found to be efficient filter media in the treatment of cyanides (462). Friese and Lehe (1359) determined the performance of coke in removing iron and carbon dioxide from waste water. Iron was reduced by 80% (from 3 mg/l) and carbon dioxide concentration was lowered from 80 to 5 mg/l. Waste slag from blast furnaces, often used as an efficient trickling filter medium, was granulated by a dry bed technique (3395).

COMPARISON TO OTHER METHODS OF TREATMENT

Knie (2517) described various methods for treating cyanide-containing waste waters, such as chlorination, acidification and aeration, and ferrous sulfate addition, in addition to percolating filters. Experimenting with lead wastes, Stones (4233) demonstrated that biological filtration would remove 30% of the lead from the settled waste, while activated sludge would remove 90%. In other experiments with copper and zinc wastes, he found that Biofilters removed 20% and 30%, respectively, as compared to removals of 80% and 60% for activated sludge (4231, 4232).

The sewage treatment plant built at Pforzheim, Germany, described by Weber (4654), had percolating filters installed for secondary treatment because of their simpler operation, lower energy requirements and greater shock-load resistance as compared to the activated-sludge process. Percolating filters were considered by Kittrell (2502) as more adaptable than activated sludge for treating varying concentrations of plating wastes. Recirculating filters were more efficient than standard filters.

Knop (2527) found that the activated-sludge process was more suitable than biological filtration for the treatment of mine drainage wastes which were ultimately discharged into streams in the Overhausen area of Germany. Tarvin (4294), from laboratory scale studies with plating wastes, compared the efficiencies of activated sludge and percolating filters. While low concentrations of metal and cyanide did not greatly affect the efficiency of the two processes, he noted that, if failure occurred, activated sludge had an advantage over percolating filters of being restarted much more easily. Walton and Smith (4597) stated, in 1958, that no satisfactory method had yet been developed for the treatment of mine drainage wastes.

POST-TREATMENT AND EFFLUENT QUALITY

Post-treatment was reported (3352, 5582) to be routinely practiced in the form of solids-liquid separation with emphasis on lagooning troublesome wastes.

SPECIAL OPERATIONAL PROBLEMS

Oeming (3215) and Bloodgood (359) observed that metal plating wastes killed organisms and reduced efficiencies in activated sludge and percolating filters. Barth et al. (203), in 1965, stressed that heavy metals in concentrations of 1 to 9 mg/l posed no serious detriment to high-rate biological filtration, as well as other aerobic or anaerobic treatment processes. Malaney et al. (2847) developed methods using laboratory techniques, such as the Warburg respirometer, to predict the effects of given metal ions on biological filtration and activated sludge.

Examination of the effects of copper on various biological treatment processes revealed that trickling filters were not seriously affected by small quantities of copper (20-25 mg/l) (4023). Horasawa (2030) experimented with copper mine waste rock as a trickling filter medium and found no appreciable effect on Aspidisca, Vorticella, Trochilia, Lionotus, Amoebae, or Zoogloea. In 1939, Spencer (4133) stated that copper and nickel plating wastes had no deleterious effects on percolating filters, but that biological purification ceased when chromium was present. However, amounts of copper larger than 25 mg/l reduced biological respiration, retarded nitrification, and released significant amounts of free acids from the hydrolysis of the copper salt (4023).

Jenkins and Hewitt (2285) experimented on a laboratory scale with chromium and its effect on bacterial filters. He found that the effects on the biofilm at 1 mg/l were slight, with a good quality effluent; at 10 mg/l, chromium retarded nitrification and organic removal and moderately reduced the effluent quality; and at 100 mg/l, chromium reduced nitrificatior by 66% and an effluent of poor quality was produced. The toxic effects of finishing and plating wastes were also examined by Tarvin (4294) on a standard percolating filter type pilot plant. Chromium was tolerated up to 4 mg/l with no ill effects. However, at 5.5 mg/l some loss of biological growth was visible. Concentrations of 1 mg/l chromate in the sewage were observed to occasionally affect nitrification (4134). The effect of heavy metals, especially chromium, was considered (5592) in conjunction with various percolating filter surfaces. Sheets (3979) examined the toxicological effects of various metals on biological treatment processes, and concluded that a shock load of 4 mg/l chromium partially damaged the biofilm, and activated sludge would withstand shock loads of 10 mg/l for 12 hours without detrimental effects. Barium, resulting from the treatment of chromium waste with excess barium chloride, appeared (4134) not to affect the percolating filter when a large amount of bicarbonate was present. Pettet (3353) also found that certain metals, sulfates, and cyanides in sufficient concentration had deleterious effects on the trickling filtration and activated sludge process. Choking of trickling filters by iron waste precipitate was reported by Cameron (598), and a comparison of trickling filters and activated sludge in the treatment of acid iron waste was discussed. The use of lath filters in combination with septic tanks for small installations was also described by Allton (58). Operational difficulties, caused by covering of the media of percolating filters by acid waste waters and oil, were alleviated by treating the filters with emulsified ortho-dichlorobenzene and breaking up the surface of the medium (1903).

Critique

Metal working industries produce wastes which may be highly acid or alkaline and toxic, plus having other non-biodegradable characteristics. Most metal finishing operations, whether it be painting, electroplating, or anodizing, usually require an alkaline treatment of some sort. Where pickling operations are used, wastes are highly acidic. When each of these two corrosive solutions is treated separately, the extreme pH's of these solutions create problems, especially where biological processes are invol[illegible]. Frequently, an industry generates both wastes and by combining the two a waste of fairly neutral pH is obtained. The main problems in the electroplating industry are the toxic wastes, particularly from chromium and cyanide. Government regulations are very stringent in the area of toxic discharge. However, vague government regulations on pollutant concentrations have sometimes allowed discharge of a waste which was not always prudent. Fairly conventional methods have been used in the treatment of metal processing wastes, as detailed in the book, "The Treatment of Industrial Waste," by Besselièvre (308). The only real advances in treating these wastes involve the economics of chemical handling. The most frequent treatment methods are by trickling filters and activated sludge, following some form of pretreatment.

SECTION XXVI

MILK WASTES

Milk wastes or the waste waters from the processing and production of milk products have generated serious pollution problems. It was remarked by Guth (1625) in 1912 that waste waters from creameries quickly underwent acid fermentation and putrefaction and were considered difficult to purify. A general review of investigations concerning treatment of milk processing waste suggested (2485) that chemical treatment was useful as a partial treatment device, but for complete treatment sand filters and trickling filters were popularly used in 1931. Levine and Watkins (2696) did considerable work on the treatment of milk processing waste by biological filtration in which bacteriological considerations were applied to explain the treatment efficiency and the functions throughout the filter handling these milk wastes. Several papers by Levine and his associates (2691, 2693, 2698, 2700) assembled much of the technology of milk waste treatment by biological filtration.

In 1954, Wisniewski (4796) reviewed various treatment processes available for treating milk processing wastes. Zack (4851) outlined a waste treatment plant that handled 175,000 gallons/day of milk processing waste waters by primary sedimentation, two-stage high-rate biological filtration, humus tank and sludge digestion, which provided effluent of sufficient quality to be discharged. The U. S. Public Health Service (5593) published a guide on types of treatment plants useful for the treatment of these wastes.

Kountz and Porges (2558) outlined government research carried out to determine the characteristics of dairy waste and explained the basic theory of the biological oxidation of dairy wastes on filter beds and in aeration tanks. The Water Pollution Research Board (Great Britain) (3287) also was active in the development of data for the treatment of milk processing waste waters for many years. The cost of construction and operation of a biological filtration system to handle waste waters from various milk processing installations in France was described by Fertin (1259).

Several specific processes were used to handle this troublesome waste. The treatment of milk processing waste was generally reviewed in 1942 by Hyde and Rawn (2161), who noted that the Mallory Process had been used. Milk processing wastes were treatable (1139) by biological filtration or by activated sludge, if the latter process was operated under carefully controlled conditions. Grewis and Burkett (1580) used a roughing filter to handle milk waste, which was combined with a treatment of poultry processing waste waters, to provide satisfactory treatment. Ellis (1157) and others (1294, 1580) used the roughing filter concept to advantage.

Preceding page blank

Levine (2691) in 1925 characterized creamery wastes as having 50% more carbohydrate lactose present than in ordinary sewage, and said that anaerobic conditions rapidly produced a drop in pH from the acid formed by the bacteria.

Lawton (2649) reported that high saline whey in milk processing wastes did not affect the development of the biofilm, providing the BOD loading was not excessive. These waste waters with a BOD in excess of 1,500 mg/l did not readily develop normal biofilm either in the presence or absence of sodium chloride. A small waste treatment plant in South Dakota was reported (4904) to treat 5,000 gallons/day of waste waters from a creamery which contributed 68 lb BOD/day. Treatment consisted of sedimentation, biological filtration and final sedimentation.

PRETREATMENT REQUIRED

The U. S. Public Health Service issued a bulletin (5593) dealing with methods of reducing milk losses and, therefore, polluting material, as well as information on effluent treatment by irrigation, percolating filters, and activated sludge. Chemical precipitation as preliminary treatment followed by biological filtration was recommended by Kershaw (2438) and Guth (1625). Pretreatment using base exchange clays and other inorganics was studied by Robertson (3649) in 1938 in treating milk processing effluents by biological filtration.

Banister and Ellison (162) gave an account of the treatment of two trade wastes, one a canning, and the other milk processing, and noted that an equalization tank and recirculation of clarified effluent could maintain a constant rate of flow so that a high capacity filter would provide the degree of treatment required. Preliminary settling was found to be unnecessary by Kennedy (2430) for the successful use of combined activated-sludge trickling filter process to handle milk processing waste.

A typical situation was a small town (population of 760) with a waste treatment plant which was required to handle waste waters from a dairy processing 200,000 pounds of milk per day (3581). The domestic sewage was screened and treated in an Imhoff tank and an Accelo-filter. The dairy waste waters enter the plant by a separate sewer system and mixed with filter effluent before passing through the percolating filter. Kimberley stressed (2485) that complete information regarding quantities, factory processes involved, and product decomposition was necessary before the design of an efficient milk waste treatment plant for a particular set of conditions could be made. For economic treatment of waste waters from the processing of milk, the loss of milk should be reduced to a total of not more than 2% of the milk received, according to Davy and Noth (895). They gave a layout of a plant suitable for complete treatment on a percolating filter combined with domestic sewage. Provision was made for recirculation of the filter effluent, and secondary tank effluent to the filter effluent.

EFFICIENCY OF TRICKLING FILTER APPLICATION

Eldridge (1129) reviewed in considerable detail various systems which were used in 1930 to treat milk processing wastes, such as (a) sand filters were desirable in areas where land was plentiful and sand was available at low cost; (b) gravel filters were advantageous for operation under nonfreezing conditions and could handle one mgad (23 gal./ft^2/day) with 93% reduction from an initial 1,600 mg/l BOD; (c) brush filters were found unsuitable due to deterioration and attack by acid forming bacteria; and (d) cinder filters produced 89% removal of wastes up to 1,740 mg/l BOD with the use of chlorination to control ponding. McKee (2919) gave an account of experiments on aeration of dairy waste waters. Aerations of milk processing waste water reduced the BOD from 260 pounds/day to 81 pounds/day. Primary sedimentation reduced the BOD by 15% and, when followed by aeration, raised this to 70%. Septic tank treatment increased the BOD removal further. Based on these results, a waste treatment plant was constructed where the waste waters were aerated, settled, and sludge separately digested, and the cost of installing and operating the aeration plant was about half of that providing treatment by biological filtration. Ellis (1157) investigated the performance of plastic media biological filters which were shown to reduce the chemical oxygen demand by 75% when operating at rates approaching 71 mgad (1,633 gal./ft^2/day) and 88 lb COD/1,000 ft^3 of media/day.

Pretreatment with high-rate percolating filters reduced (896) the BOD of waste waters from 826 to 396 mg/l before milk wastes of 13,333 gal./day were discharged to the sewage treatment plant. A total combined flow of 74,900 gal./day was treated at the sewage works to reduce the resulting 323 mg/l BOD of the mixed influent to 65 mg/l. Chemical-biological filtration of milk processing wastes and other trade wastes indicated, according to Brühne (509), that the chemical treatment reduced the permanganate demand by 79% and the BOD by 93%, with further improvements affected by biological treatment. Wisely (4782) reported on a combined trade waste comprised of 46% milk waste and 9% brewery waste which overloaded the treatment facility, but operational changes to incorporate chlorination and recirculation resulted in efficiencies as measured by suspended solids reduction of 350 to 45 mg/l and BOD reduction of 491 to 54 mg/l.

Municipal sewage treated in combination with milk processing waste was (3529) chlorinated, comminuted, the pH raised by lime addition, followed by primary sedimentation, trickling filtration, and final sedimentation. This plant performed with an average BOD removal of 92.2%. It was noted (5593) that percolating filters would handle diluted milk processing waters at 0.5 to 3.0 lb BOD/yd^3/day (18.5 to 111 lb BOD/1,000 ft^3/day) at an efficiency of 70 to 90% BOD removal. When compared to well operated activated-sludge systems, which were capable of BOD removal as high as 99%, other considerations for the use of biological filtration must be used, such as economics and less supervision.

Wieselberger (4721) briefly summarized the literature of the use of alternating double filtration on milk processing wastes and stated that a high rate percolating filter in Bavaria produced 90% reduction of BOD and with lower loads an effluent of 20 mg/l BOD or less was obtained. As was typical of many, Rumpf (3782) used alternating double filtration in 1953 to treat milk waste which had a BOD of 450 to 1,280 mg/l and produced an effluent BOD of 3 to 10 mg/l.

COMPARISON OF OTHER METHODS OF TREATMENT

Bettels (311) reported in 1928 that milk processing waste waters could be successfully treated in percolating filters or discharged directly into any stream affording 1:100 or 1:150 dilution. The characteristics of dairy waste waters in Germany in 1933 implied mechanical and biological methods for treatment, with the choice governed by local conditions (1057). A submerged trickling filter, as designed by Dewes (942), to handle milk processing effluent to adequately reduce the pollution did not develop metabolic products which were toxic to aerobic organisms in normal secondary operations, such as percolating filters or activated sludge.

Based on a review of recommendations by the Royal Commission (Great Britain) of the late 1800's, and the activities of the Water Pollution Research Board, Calvert (586) described the treatment of milk processing wastes by alternating double filtration. Later, Jenkins (2282) detailed successful treatment of milk processing waste by alternating double filtration.

Percolating filters and activated sludge were discussed as treatment systems by Barritt (194) for the treatment of milk processing wastes. Either process was adaptable after preliminary treatment and followed by humus tanks, but slight advantage was given to activated sludge due to its inherent ability to take advantage of higher temperature waste. Cantinieaux (613) also investigated the use of two-stage biological filtration and activated-sludge processes to treat milk processing waste and concluded that both methods were satisfactory.

POST-TREATMENT AND EFFLUENT QUALITY

Falkenhain (1235) reported in 1947 after reviewing fermentation, biological filtration, surface irrigation, spray irrigation, and fish ponds to treat milk processing waste waters that, from the point of view of purification and utilization, the best methods were to distribute the waste waters on land through spray irrigation during ten months of the year and by surface irrigation during the winter. Imhoff (2195) discussed the advantages of recirculation of effluent on trickling filters which were handling milk processing wastes. Post-treatment by slow sand filtration was popular in 1938 as indicated by Robertson et al. (3649).

SPECIAL OPERATIONAL PROBLEMS

Occasional chlorination (1129) was required to control ponding. Rapid acid fermentation caused problems in long sewer lines (2691). Combined domestic and milk processing wastes required special attention (3529), such as chemical treatment by chlorination and lime for control of pH and odor.

Critique

Milk wastes, generally characterized as high in dissolved organic matter, exerting relatively high BOD's, and initially neutral in pH, but readily susceptible to acid fermentation, have been found to be extremely amenable to treatment by biological filtration. This success and the numerous plants in operation, ranging in size from very small to large industrial complexes, have been reported in considerable detail.

A very small fraction of the literature available was reviewed here. Sufficient evidence was presented to indicate that biological filtration following pretreatment in the form of pH neutralization, solids capture, and partial disinfection was satisfactory. Trends were noted in the literature, e.g., prior to 1930 treatment of milk wastes was difficult and when admixed with domestic sewage undesirable results of plugging and nuisance conditions developed. With increases in development effort, the operational experience for treatment of these wastes was successful.

As biological filtration was demonstrated effective, other methods such as activated sludge were attempted and on occasion were quite successful. Due to the readily biodegradable nature of the waste, preliminary aeration has been valuable in removing initial BOD. Biological filtration was operated under considerably higher than normal saline conditions which were developed at certain milk processing plants producing cheese.

The literature showed some overlap of investigators' efforts, which may be viewed to substantiate further the efforts of each of the investigations. The conclusions reached by the investigators indicating that only activated sludge or biological filtration or some other method should be used for the treatment of milk processing waste may not be well founded. It is suggested that the decision for the use of one or more of these processes would be more rationally dictated, as some investigators have noted, based upon waste characteristics. Most importantly, economic factors, such as availability of land and operational personnel qualifications, must enter into the decision. It may generally be concluded, however, that biological filtration with limited pretreatment or little flow time between the source and the treatment plant will provide adequate treatment for most milk waste installations.

SECTION XXVII

PHARMACEUTICAL AND FERMENTATION WASTES

The importance of pharmaceutical and fermentation wastes has been recognized by groups such as The American Chemical Society, which sponsored symposia on various aspects of water pollution control and specifically on fermentation waste disposal (2059). Genetelli et al. (1452) outlined an approach to selecting an industrial waste treatment system to treat waste waters from the manufacture of pharmaceutical chemicals which involved a survey of the receiving body of water, examination of individual waste streams within the plant, experimentation on the possibility of biological treatment of one or more of the waste streams along with other procedures to determine the design criteria for a plant.

Pharmaceutical industrial wastes were treated (2815) by a local sewage works and investigations of these wastes indicated that the greatest effect on the works was the waste from the manufacture of tetracycline. Molof (3058) reviewed pharmaceutical waste treatment by activated sludge or biological filtration, and Hurwitz et al. (2134) described the treatment of penicillin and streptomycin waste waters by biological filtration. Chipperfield (681) summarized waste treatment developments, with emphasis on plastic media for biological trickling filters, which were proven economically sound for the treatment of fermentation and yeast manufacturing waste with savings on capital expenditures of 25 to 55%.

Rudolfs commented (3764) on the operational factors of characteristically high organic wastes such as may be found in fermentation industries. These wastes usually contained less suspended matter but more soluble organic matter than sewage. Physical or chemical treatment was not as successful as biological treatment, and many of the wastes required additional nitrogen source. Penicillin wastes were characterized in 1949 by Heukelekian (1920) to have a pH valve between 2 and 2.5, a BOD of 2,150 to 10,000 mg/l for the spent broth, wash waters having a BOD of from 210 to 13,800 mg/l, with various organic and inorganic compounds used in the process as well as some suspended material. Howe and Coates (2056) characterized waste waters from the manufacture of antitoxins, anti-sera and vaccines as containing total solids concentrations of 4,000 to 8,500 mg/l, volatile solids of 3,000 to 7,500 mg/l, BOD 1,000 to 1,700 mg/l, and alkalinity 600 to 800 mg/l. The waste waters, 15,000 gallons/day, including blood from test animals and wash water as well as waste chemicals and animal excreta, were generally red.

A French publication (4955) reported the characteristics of waste waters from the manufacture of penicillin, streptomycin, aureomycin, which agreed well with the comments by Heukelekian

(1920). Muss (3142) and Paradiso and Howe (3283) characterized the combined waste waters from the manufacture of penicillin, primarily from spent broth, wash water, and total solids of 12,500 mg/l. Aureomycin waste waters, 63,000 gal./day (1593), were combined with sanitary sewage and storm water totaling about 2.5 mgd, and the resultant solution had a BOD of 46 to 150 mg/l, total solids of 1,500 mg/l, suspended solids 200 mg/l, and a pH of from 2.5 to 8, and was highly colored.

Dlouhy and Dahlstrom (983) tabulated typical fermentation waste strengths which ranged in BOD's from 200 to 50,000 mg/l with suspended solids from 30 to 5,000 mg/l. The quantities of yeast waste were reported by Kiby (2471) as being great, e.g., a small factory using 5,000 to 6,000 kg (5.5 to 6.6 tons) of molasses per day produced more than 100 m^3 (130 yd^3) of waste per day. The wastes were characterized as having variable quantities of alcohol, suspended solids, and salts, and were treated experimentally by anaerobic fermentation followed by several stage settling and biological filtration.

PRETREATMENT REQUIRED

Process changes, such as that noted by Kiby (2471), involved in the manufacture of yeast, altered the effluent so that previous treatment methods were modified or discontinued. Preliminary treatment at the source was necessary, e.g., neutralization and distillation of the solvent used to extract the pencillin (1098). Due to intermittent discharge of the waste, a schedule of discharging was coordinated with recirculation at the waste treatment facility to assure adequate degradation of the spent metabolite from the penicillin manufactured.

Wittmann (4800) reported that waste waters from the production of antibiotics were treated partially by evaporation and by activated sludge, and later by high rate biological filtration, to produce a satisfactory effluent. Griffin (1593) reported on the treatment of aureomycin waste to which lime was added to give a pH of 10 prior to discharge to a lagoon. The lagoon was later replaced by a plant consisting of a holding and aeration tank, primary and secondary sedimentation tanks, and recirculating trickling filter.

Combined treatment with activated sludge and percolating filters was used successfully by Black and Fairall (342) for the treatment of pharmaceutical wastes with primary emphasis on biological filtration. This system was also described by Horne and Rinaca (2036) and others (3058) to provide adequate treatment for combined pharmaceutical waste.

Because of overloaded conditions of biological filtration plants, Edmondson (1115) indicated that fermentation wastes from the manufacture of antibiotics be pretreated by triple-effect evaporation at the rate of 2,500 gal./hr, with the condensate then being treated by aeration and biological filtration. Harvey (1783) noted that septic tanks were used as preliminary treatment ahead of trickling filters on wastes from yeast plants to provide successful treatment in Scandinavia. Anaerobic pretreatment was reported by Rudolphs (3764), Krige (2571), and Wittmann (4799) to reduce the BOD significantly, with the effluent amenable to further secondary treatment. Lagoons were occasionally used for pretreatment, and their successful operation overshadowed the effectiveness of percolating filters and activated sludge, which were then discontinued (4433).

EFFICIENCY OF TRICKLING FILTER APPLICATION

Two-stage biological filtration was reported by Tompkins (4430) to reduce pharmaceutical and antibiotic waste by 95 to 98% BOD. Three-stage biological treatment, outlined by Howe (2059) to treat antibiotic production wastes, reduced the BOD 90 to 95% and removed antibiotic activity completely.

Heukelekian (1920) investigated chemical treatment, anaerobic digestion, activated sludge, and biological filtration. He concluded that digestion, followed by biological filtration through coarse medium then fine medium, produced a final effluent with a BOD of 35 to 40 mg/l from an influent of 2,150 to 13,800 mg/l. Antitoxin and vaccine wastes were treated by an Imhoff tank and a high-rate percolating filter (2056). The effluent characteristics were 508 mg/l suspended solids, 12.3 mg/l BOD, an absence of color and odor and an alkalinity below 318 mg/l from an influent having 4,000 to 8,500 mg/l total solids, and 1,000 to 1,700 mg/l BOD. According to Reimers et al. (3551), wastes from the manufacture of antibiotics, sulfa drugs and vitamins were usually treated by evaporation and incineration. Weaker wastes were combined with sewage and adequately treated by high-rate filtration with 80% BOD removal on a single stage operation loaded at approximately 2 lb/yd^3/day (74 lb BOD/1,000 ft^3/day). A penicillin waste with a BOD of 4,900 mg/l, a permanganate oxygen demand of 2,930 mg/l, a pH of between 6 and 7 and containing 26,800 mg/l total solids was treated to 99% removal of the BOD, producing an effluent of 30 mg/l BOD, if the loading were diluted to 0.5 lb BOD/yd^3 (18.5 lb BOD/1,000 ft^3/day). Preliminary treatment of a pharmaceutical plant manufacturing antibiotics by lime and dilution 1:1 with river water plus primary sedimentation allowed high-rate biological filtration with secondary sedimentation, followed by chlorination, to produce 70% removal of suspended solids and 35 to 50% BOD removal (1464).

The treatment of compressed yeast wastes was studied by Rudolfs and Trubnick (3769) over five years on trickling filters and, with loadings of 300 to 2,800 lb BOD/ac-f/day (276 lb BOD/1,000 ft^3/day), there was a marked decrease in removal efficiency. They (3767) also treated waste waters from the production of yeast combined with sewage at 1 mgad (23 gal./ft^2/day) on a biological filter. Concentrations of 400 mg/l BOD were reduced by 80 to 87%; with higher concentrations efficiency was sharply decreased. Active nitrification occurred with all concentrations and the rate increased on passage through the filter.

Liontas (2723) described an industrial waste treatment unit also treating sanitary sewage. The waste waters contained inorganic acid, fermentation waste, salts, acetic solvents, and other aliphatic and aromatic compounds, and had, after preliminary treatment, a BOD of 10,000 mg/l. The overall reduction in BOD averaged 98%. A typical yeast plant effluent was treated by Rudolfs (3764) anaerobically in three stages over 3.25 days on an influent BOD of 5,150 mg/l, producing an effluent with 77.5% reduction. Another system involved lagoon storage, followed by treatment in covered percolating filters at the rate of 24 mgad (552 gal./ft^2/day) to reduce an influent BOD of 200-250 mg/l by 70%.

COMPARISON TO OTHER METHODS OF TREATMENT

An acid fermentation waste was described by Krige (2571) as molasses slop which had an average BOD of 1,000 mg/l and total solids of 8,000 mg/l. Possible methods of treatment investigated were evaporation, anaerobic digestion, and passage through percolating filters. Previous experience indicated chemical coagulation was of little or no value. Penicillin waste waters with a BOD of 12,000 mg/l, a pH of 2 to 3, and suspended solids of 12,000 mg/l were treated by Wittmann (4799) with anaerobic digestion and biological filtration, and it was concluded that the latter was the better method.

Waste waters from a yeast factory with a BOD of 5,000 to 9,000 mg/l were digested anaerobically, and experiments on aerobic systems by Merkel (2976) indicated that two-stage treatment was successful but single-stage was susceptible to a strong growth of fungus. Jensen (2316) described operations in the production of yeast similar to that of Kiby (2471). He observed that preliminary treatment, using anaerobic digestion followed by lagooning, prepared a waste which, when treated on percolating filters, produced little suspended matter in the effluent. Humus tanks were unnecessary. The BOD was reduced from 8,600 mg/l to 100 mg/l with a pH going from 4 to 7.8 as a result of this treatment.

Tooloose et al. (4433) reported on a treatment plant development in which it was shown that a properly operated lagoon would handle fermentation waste waters, provided that sudden changes in loading were avoided and seasonal efficiency could be tolerated. This method was just the opposite of that selected by Vogler (4545), in which a fermentation waste was originally clarified, treated on percolating filters, followed by an aeration unit and final sedimentation tanks with some reliance on chlorination and sludge lagoons.

Jackson (2251) preferred biological filtration to activated sludge for the treatment of fermentation waste due to its more economical operation and lower sensitivity to shock loads from the fermentation industry. Bopardikar (407) experimented with the use of algae as an alternative method of treatment to conventional biological filtration and other processes for antibiotic production effluent, and found the method to be less expensive than conventional ones. Deep well injection has been practiced by Cushman and Hayes (849) and by Gurnham (1624) to handle the disposal of pharmaceutical wastes as an alternative to biological methods. However, Cushman and Hayes (849) also investigated various modified biological treatment systems in combination with chemical wastes and domestic sewage. Based on pilot studies it appeared that all the waste waters were amenable to treatment by biological filtration.

POST-TREATMENT AND EFFLUENT QUALITY

Sisson (4043) reported that treatment by two-stage biological filtration, following preliminary neutralization, flocculation, and sedimentation, conditioned pharmaceutical waste waters so that they could be used for ground water replenishment by pond percolation. Tompkins (4430) found the BOD of the pharmaceutical waste effluents from two-stage biological filtration with recirculation was reduced by 95 to 98%. Jensen (2316) stated that percolating filters following anaerobic digestion removed solids to the extent that a post-treatment humus tank was not required.

The effluent from the percolating filter for yeast waste treatment showed (2471) a reduced ammonia content, a high nitrate and nitrite, dissolved oxygen, and did not decolorize methylene blue at 20°C, indicating stability. The effluent was discharged after dilution with untreated cooling water.

Experiments (2571) on the use of two-stage enclosed percolating filters treating a diluted fermentation waste with a recirculating ratio of 10:1 indicated that for the effluent to to be treated to the degree necessary 30,000 yd^3 of filtering medium would be required. A greater volume of water or sewage than was available would be needed for dilution.

SPECIAL OPERATIONAL PROBLEMS

Overload of the plant during operation was experienced occasionally, e.g., Hamlin (1691) stated that 10,000 gallons of yeast factory effluent was dumped into a sewage system treating approximately 100,000 gallons per week which severely overloaded the trickling filters. The waste stream had to be diverted to another sewer and the filters quickly recovered. Wett and Hartshorne (4696) noted that an overloaded condition of a pharmaceutical plant was relieved by the installation of plastic media in the trickling filter oxidation tower. The capacity of treatment was doubled and a 99% reduction in BOD was maintained.

Patil et al. (3310) had difficulty using biological filtration for the treatment of complex waste waters resulting from the manufacture of synthetic drugs, even when procedures of dilution and some acclimation were employed. Kiby (2471) reported on process modifications which were made in 1934 for the manufacture of yeast which drastically changed the waste water quality and it was noted that sedimentation followed by discharge into lagoons or field irrigation was unsatisfactory as the method of treatment of these waters.

Pitts (3390) reported that loadings of 5,000 lb BOD/ac-f/day (115 lb BOD/1,000 ft^3/day) had been applied to biological filters, but with prolonged operation ecological imbalances could arise and plug the filters during the treatment of pharmaceutical wastes. Problems due to ponding in the trickling filter because of too fine a medium were also noted (1464) in the treatment of pharmaceutical waste and further studies were to be conducted on combined treatment by activated sludge followed by a percolating filter.

Critique

Fermentation wastes, other than those found under the section on brewery and distillery wastes, have characteristics which are similar to pharmaceutical wastes in several aspects and treatment responses. Considerable information was published on the characteristics of specific and general waste streams from several different geographical areas. Agreement on characteristics was fair. Conclusions in the type of treatment which should be used to handle these wastes were sometimes conflicting. However, once again, local circumstances from the standpoint of effluent quality and economics played a major role in the selection of a treatment process. Biological filtration was useful in the treatment of pharmaceutical wastes, but not completely satisfactory. Occasions were reported where advantageous use of anaerobic digestion followed by aerobic treatment, such as biological filtration, produced an effluent of high quality.

Based on this review, biological filtration should be used in conjunction with other processes for the treatment of fermentation and pharmaceutical wastes. Problems arising with antibiotics and other drugs in the biological systems have been met rather routinely. There was no concerned indication in the literature of any relationship between viral production or transfer in treating wastes from vaccine production facilities. It may appear at first glance that the injection of effluent from pharmaceutical waste treatment facilities into ground water basins is a bad practice. However, the limited travel distance of most life forms in alluvial material, clays, or other subterranean aquiferous materials must be considered. Biological filtration was shown to be effective for the treatment of these high organic content wastes. The requirement for extensive land area for biological filtration to achieve the required quality of treatment may, in part, be eliminated by fabricated medium and other process modifications.

SECTION XXVIII

PULP AND PAPER WASTES

The use of biological trickling filters on pulp and paper mill waste was reported often since the early 1900's (2079). To evaluate the effectiveness of the treatment and characterize the waste, McGowan (2911) in 1921 devised an indexing system based on dissolved oxygen absorption. Paper mill wastes had an index of 22, distilleries 33, tanneries 22, and printing and dyeing 25. Sciver (3926) criticized McGowan's formula and suggested that trade wastes, such as from the pulp and paper industry, increased the suspended solids content of the sewage and this characteristic made sedimentation more difficult. However, waste waters from a paper factory in Europe (4654) contained little fibrous material, but were heavily colored.

Southgate reported (4118) the characteristics of a paper mill waste to be: (a) 18,000 gal./day of spent liquors and washings from digestions of rags and cold washings from straw and wood with a BOD_5 of 4,600 mg/l and 1% alkali (as Na_2CO_3); (b) 100,000 gal./day waste water from potchers and concentrators with a BOD of 250 mg/l and neutral; and (c) an average of 12,000 gal./hr of waste water from paper making machines with an average BOD of 110 mg/l and neutral or slightly alkaline. The mixed waste waters after sedimentation had an average BOD of 230 mg/l, with liquors containing spent lye washings from the digested material being the most difficult to treat. About 540,000 gallons of waste water were produced from a process which required 30,000 gal./ton of raw materials per day (4118). Waste water from the cardboard or hard board manufacture was found by Schmidt (3873) to have a BOD_5 of 338 mg/l, a permanganate demand of 1,580 mg/l and a phenol content of 3 to 4 mg/l with the pH being 3.6 to 6. Lime coagulation, superphosphate addition, and recirculation were necessary to alter the characteristics of the cardboard waste waters for efficient biological treatment. Mueller and Schulz (3109) reported on the characteristics of the waste water resulting from the bisulfite process to have a pH of 3.8 to 6.7, with a permanganate value of 790 to 3,475 mg/l, the BOD_5 of 65 to 368 mg/l, and with nutrient addition required for trickling filter or other biological treatment. Eden et al. (1099) discussed the three types of waste waters from a paper mill: (a) black liquor at 13,200 gal./day being comprised of spent lye, first wash water, and flow washings from the digester house; (b) strong washings amounting to 55,200 gal./day composed of latter stage wash water and bleaching of digested hemp; and (c) 1.65 mgd composed of washing, bleaching and beating of materials other than hemp, and discharges from paper machines, lime sludge from the water softening plant, and some storm water. It was reported by Holderby (1977) that the waste waters from the manufacture of cellulose by the sulfite process contained lignin, sugars, sulfur dioxide, and organic acids. Krussman (2579) outlined

Preceding page blank

pilot plant studies for treatment of waste waters from a paper mill. Waste water from this plant included rag cooking liquor, wash water, white liquor and power plant discharge.

Gehm (1442) concluded that de-inking waste waters were not treated satisfactorily by trickling filtration because of their high alkalinity. He also concluded that percolating filters were not suitable for treating waste waters from kraft mills due to nonbiodegradable materials.

While the characteristics of the waste were investigated, Tyler et al. (4491) studied the types of organisms most suitable for seeding filters to treat waste water from the sulfite process. By seeding with various organisms and molds, and then removing the sulfur dioxide, they successfully treated waste liquor on percolating filters. The American Society of Civil Engineers formed a task force to investigate the biodegradability of alkaline waste waters (4915) and it was concluded that alkaline waste could be treated biologically without neutralization although less oxidation would occur at high pH values. Because some paper mill wastes contain various turpentine mixtures, polyvinyl chloride plastic medium (4970) was used in biological treatment of kraft pulping waste waters as well as in other applications(643). Horlock et al. (2034) and Eden et al. (1099) agreed that a supply of nitrogen, such as sewage or ammonium sulfate, was necessary to maintain a stable flora population in trickling filters. Paper mill effluents became a source for the recovery of materials of economic value in India (1615). However, the effluent still had 200 mg/l BOD and 300 mg/l suspended solids and, from processes other than the sulfite process, required further treatment consisting of sedimentation, with or without coagulation, and some type of biological filtration. Waste waters, from the preliminary treatment of flax fibers for the preparation of specialty papers, consisting of spent cooking liquor and other cleaning waters, were discharged at the rate of 30,000 gal./day, of which 13,000 gal./day was spent black liquor with an overall BOD_5 of 30,000 to 40,000 mg/l and 130,000 to 140,000 mg/l suspended solids with 0.3 to 0.5% caustic soda (3226). A specialty paper manufacturer produced 1.3 mgd waste water which had a BOD of 250 to 300 mg/l and contained 15 to 20 lb suspended solids (9).

The waste from the steam distillation of wood hydrolysis plant was described by Black and Minch (340) to vary greatly in volume and in BOD and to contain soil, wood fibers, tannin, rosin, oil, solvents, and furfural. Anaerobic digestion and percolating filters were used by Roznoy (3708) to treat cellulose acetate wastes, which were composed of acetic acid, acetate, cellulose acetate fines, and sugars from hydrolysis. The waste waters were characterized by

BOD_5 of 2,700 to 3,900 mg/l, pH of 3.5 to 4.3, and total solids of 9,700 to 13,200 mg/l. After biological filtration, the waste water from a wood hydrolysis plant was shown by Tkachenko (4396) to contain appreciable amounts of wood and gum sugars, acetic acid, and traces of formic and levulinic acid. As a follow-up to this work, he (4397) also studied the effect of temperature on the microorganisms in percolating filters treating waste waters from hydrolysis plants. He showed that exposure to low temperature for several days had no effect on the viability of the organisms.

Successful removal of 27 to 700 mg/l of furfural in a spent alkaline fermentation liquor with a BOD_5 of 400 to 500 mg/l was reported on a wood hydrolysis plant waste by Drublyanets and Ivanova (1033). They also offered an explanation of the removal kinetics during biological oxidation of hydrolysis plant effluent (1034). Detailed investigations of the waste water from wood hydrolysis plants by Tkachenko and Yudina (4398) indicated that Escherichia coli did not survive the strong disinfecting action of these waters. A large number of yeasts have been isolated by Tkachenko (4399) from percolating filters treating waste waters from wood hydrolysis plants.

PRETREATMENT REQUIRED

Because of the general characteristics of pulp and paper waste, usually some effort was required to make the waste amenable to biological treatment. Ackerman (9) stated that sedimentation and equalization in a lagoon prior to biological filtration were desirable based on results of pilot plant studies. Preliminary treatment of the waste in a save-all yielded an effluent which could be treated satisfactorily by biological filtration according to Richey (3593). A Spaulding Precipitator was used by Stahl (4162) to remove 44 to 68% of the suspended solids in paper mill waste water effluent prior to filtration. While sand filtration proved unsatisfactory because the solids rapidly clogged the bed, quiescent settling and withdrawal of the supernatant liquid through fine screens was reported by Geer (1439) to be adequate in a tank on the fill and draw method operated with a detention time of 1.5 hours. Burton (544) was issued a patent on a system which involved entrapment of colloidal particles by prewetted natural bark fibers. The effluent of this patented process was treated in special percolating filters. An inclined screen was used by Howard (2052) with the filtrate being stored in tanks so that uniform liquor concentration could be obtained for the paper mill waste stream.

The possibilities of reusing the soda in washing waters and the black water in beaters as well as treating the waste waters from paper mills by sedimentation, with and without coagulants, were discussed by Southgate (4118). Hodge (1965) supported the concept of reuse of the water and recovery of byproducts from the pulp and paper waste streams, as well as treatment in lagoons, chemical coagulation and sedimentation. Eldridge (1140) stated that nine tons of material per day were recovered from a flow of 15,200 gph of waste when 95 mg/l alum were added. Seven tons of usable materials were recovered from a dry paper machine with 600 pounds of alum added per day to a 85,600 gph flow of waste.

Dilution with fresh water or effluent and chemical addition was a common practice (1034, 3226). The additions of ammonium sulfate and superphosphate as nutrient sources were also common, as for example, Drublyanets and Ivanova (1034), as well as others (1099, 3873). Coagulation of mill waste waters with alum, calcium chloride, or ferric chloride was proven impractical by Oldaker (3226), as large amounts of sludge were produced and the maximum reduction of BOD was only 50%. Eden et al. (1099) used neutralization and dilution as well as dechlorination and addition of nutrient salts to handle waste waters from a mill manufacturing special grades of paper from hemp, linen, cotton, and other textiles. A two-stage biological treatment process in which activated sludge was followed by biological filtration provided 80% reduction in BOD; yet Schmidt (3873) stated that coagulation with lime reduced the BOD by 40% and permanganate value by 20%. One type of pretreatment frequently practiced was described by Black and Minch (340) in which the waste was segregated into four distinct elements, where controlled filtration, sedimentation, coagulation, screening, as well as biological filtration, could be effectively used to provide the treatment required.

Studies by Rüffer (3777) on coagulation of the wood process waste waters with lime indicated that a pH value of about 11 was required to create the large flocs in the hard fiberboard waste stream necessary for good removal. Gascoigne (1422) discussed the utilization of chlorine for the treatment of white water from paper mills. Hommon (2001) commented in 1916 that coagulation of straw board waste with aluminum sulfate, followed by rapid filtration, was not very successful. In 1910, Clark (692) decolored paper mill waste by intermittent sand filtration for a period of time, but best results were obtained by adding calcium hydroxide and ferric chloride in an amount not over one ton per million gallons treated. However, Merryfield (2979) later reported that waste from the flax industry was precipitated with 0.5% lime solution, and was followed by biological filtration. Rohde (3669) described the successful handling of an industrial waste problem which involved two paper factories by using iron sulfate and lime added to the sewage entering the sedimentation tank and allowing the sewage to be aerated in a preliminary section of this tank. This effluent was thereby rendered amenable to biological filtration on enclosed filters containing a media bed of lava slag four meters (4.38 yd) deep.

Anaerobic digestion before discharge to a sewage treatment plant was used by Rohde (3671) on tannery and straw board mill waste in Germany. As a preliminary or partial treatment of straw board waste water, digestion of a mixture of waste waters and digested sludge from domestic sewage produced an anaerobic flocculant sludge which settled easily and had strong adsorptive properties (2353).

Hydrolysis plant effluents were diluted with fresh water or low BOD effluent, and nutrient added to aid biological treatment (3166). In treating the waste waters from thermal treatment of wood, aluminum sulfate was the best coagulant tested by Busnita (553) and with the addition of nutrients gave sufficient pretreatment so that admixtures of the waste water with sewage at a ratio of 1:3 could be handled by biological filtration.

EFFICIENCY OF TRICKLING FILTER APPLICATION

The efficiency of the biological trickling filter process was measured over the years by several different techniques, for instance, McGowan (2911) and Mueller and Schulz (3109). During his pure culture studies, Tkachenko (4399) found that the yeast Candida tropicalis was able to reduce the BOD of wood hydrolysis plant waste water by 61 to 64%. Investigations with acid sulfite liquor by Holderby (1977) determined that BOD_5 was reduced from 60 to 65% with loadings of up to 3.03 lb BOD/yd^3/day (112 lb BOD/1,000 ft^3/day). He concluded that the percolating filter had the ability to reduce the BOD of sulfite liquor mixtures by more than 75%. Mueller and Schulz (3109) reduced by 70 to 75% the BOD of the waste water from the cellulose industry's sulfite process by the trickling filter.

Laboratory scale apparatus was applied to treating cellulose acetate waste. Roznoy (3708) found that, by double filtration with an applied load of 2 lb BOD/yd^3/day (74 lb BOD/1,000 ft^3/day) and the recirculation ratio of 3:1, the BOD decreased from 1,170 mg/l to 174 mg/l in the first filter. This BOD was further reduced to 82 mg/l in the second filter under the optimum loading limit of 1.6 lb BOD/yd^3 (59 lb BOD/1,000 ft^3/day). Based upon a general review of methods in treating paper mill effluent, Horlock et al. (2034) reported the improved efficiency obtained by using alternating double filtration and recirculation of effluent as well as supplying nitrogen by sewage or ammonium sulfate addition.

During experimental studies by Tyler et al. (4491), the filters were loaded at 25 lb BOD/yd^3/day (925 lb BOD/1,000 ft^3/day), and it was shown that approximately 77% of the sugars and 49% of the BOD were removed from the sulfite process waste water. When the load was dropped down to 10 lb/yd^3/day (370 lb BOD/1,000 ft^3/day), the corresponding reductions were 80% of the sugars and 76% of the BOD. Further studies done at elevated temperatures and higher concentrations of sulfite waste liquors led the authors to the conclusion that operation above 25°C was not economical and that as high as 80% sulfite waste liquor could be treated on the filters without adversely affecting the efficiency of treatment.

Eighty-five percent removal was experienced on chip board waste on a low rate trickling filter by Richey (3593) with an organic loading of 15 lb BOD/1,000 ft^3/day and a hydraulic load of not more than 1 mgad (23 gal./ft^2/day). By using a 1:1 recirculation ratio of effluent at the same organic loading and a total hydraulic loading including recirculation of 2 mgad (46 gal./ft^2/day), he achieved 93% removal of the BOD. In pilot plant investigations on kraft pulp mill effluent in Poland, Nowacki and Pilotek (3207) obtained optimal results with a BOD loading of 1,420 g/m^3/day (89 lb BOD/1,000 ft^3/day). A hydraulic loading of 1.53 m^3/m^2/day (37.5 gal./ft^2/day) was used to provide reductions in BOD and permanganate demand of 80% and 17.5%, respectively. The authors noted, however, that the removal of color was poor and that recirculation of effluent did not improve treatment efficiency.

Voight (4546) described a two-stage biological process treating straw board waste waters which reduced a BOD of 2,500 to less than 60 mg/l within the effluent suspended solids of less than 50 mg/l. The results of a study by Brébion (449) indicated that ion exchange, filtration, and anaerobic digestion processes were inapplicable to industrial scale situations. Activated sludge and biological filtration appeared feasible enough to treat waste from industrial processes permitting 80 to 90% reduction in BOD in 36 to 48 hours.

Several packing arrangements of the media in biological trickling filters have been used on pulp and paper mill effluent, e.g., Renzi (3560), Minch et al. (3024), Crawley and Brouillette (815), Follett (1305), Egan and Sandlin (1119), Eckenfelder and Barnhart (1082), and Middlebrooks and Coogan (2993). Results from these studies using fabricated media indicated BOD loadings of 3.5 times that of conventional rock could be used (3560). BOD removal was 90% for fine paper effluent (1305). Loadings of 750 lb BOD/1,000 ft^3/day were applied without impairing the efficiency of the operation and gave removals as high as 370 lb BOD/1,000 ft^3/day (1119). The tower oxidation approach was reported by West (4680) and Ganczarczyk et al. (1405) as desirable for aeration and for the reduction of BOD and concentration of oxidizable substances in the mixture of pulp wash water and bleaching effluents. Influent hydraulic loads of 1 gpm and recirculation of 7 gpm were reported by Middlebrooks and Coogan (2993) to effect 50% BOD removal on the plastic filter media. When toxic shocks did not occur, an average of more than 60 to 70% of the BOD was removed at surface loadings of 5.7 gpm/ft^2 or 370 mgad (8,600 gal./ft^2/day). They favored fabricated media for roughing filters as efficient treatment devices capable of removing 60% BOD at 3.7 gpm/ft^2 (5,328 gal./ft^2/day) and a recirculation rate of 2 gpm/ft^2 (2,880 gal./ft^2/day).

Many of the laboratory and pilot investigations on the biological treatment of paper mill wastes have been expressed in terms of mathematical relations, e.g., West (4680). Several of the mathematical models dealing with paper mill effluent data were evaluated statistically by Robertson (3647). Additional mathematical discussion was previously covered, but it is of interest to note that the relationship described by Galler and Gotaas (1397) was found to best fit the prediction of the trickling filter performance while operating on paper mill waste.

COMPARISON TO OTHER METHODS OF TREATMENT

The troublesome characteristics of paper mill and wood hydrolysis waste were indicated by the pretreatment required and the efficiency of the trickling filters. Many methods were investigated, and Grant (1538) discussed the mechanical, chemical, biological, and preventive methods for reducing the strength of the waste before it reaches the receiving water. Biological filtration was generally preferred to activated-sludge treatment in spite of the large plant required, but a closed circuit system of counter washing was strongly recommended. Blosser (366), under the auspices of the National Council for Stream Improvements, worked with aerated lagoons and found that four days' aeration was required for an 80% BOD reduction on de-inking waste and that the sludge produced and the quality of the effluent were similar to those from the activated-sludge process.

In a literature survey, Rennerfelt (3558) reviewed the composition of waste water from forest product industries, biological treatment, aerated and nonaerated stabilization lagoons, percolating filters and the activated-sludge process. A review by Gleeson (1486) included methods of treatment, such as the activated-sludge process, biological filtration, aeration utilizing the tendency of liquor to foam and accelerate oxidation, fermentation with production of fodder yeasts or alcohol, evaporation with or without burning, disposal in lagoons, the Howard process of coagulation with lime, hydrolysis at high temperatures and pressures, and ion exchange. In 1950, Holderby and Wiley (1978) reviewed the result of the work of the Sulfite Pulp Manufactuers' Research League, Inc., as: (a) the activated-sludge process would reduce the BOD of the waste sulfite liquor by 95%; (b) percolating filters would reduce it by 65%, and under favorable conditions 75%; (c) contact aeration would reduce it by 70 to 75%; (d) aerobic methane fermentation was not satisfactory; and (e) promising results were obtained from the cultivation of yeast. Each of these processes had its limitation under a given set of circumstances and must be evaluated with this consideration.

Studies by Brébion (449) in France showed that ion exchange, filtration and anaerobic digestion did not have the advantages of biological filtration. A porous partition-type apparatus was compared by Brébion and Huriet (452) to conventional percolating filters, which was an advantage to the trickling filter process due to lower construction cost. In contrast to other work (449), an anaerobic filter, in which the flow of waste water was upward through the filtering material, was successfully used by Dewes (942). A phosphate-impregnated, honeycombed asbestos paper medium was used by Quinn and Fronzoso (3495) to reduce the BOD by 61% at the greatest flow and 86% at the lowest flow, which was ten times greater per unit than the flow generally applied to trickling filters. Tabb (4288) has developed a process for treating dilute waste waters from mechanico-chemical processes of digestion by passing carbon dioxide through the waste waters to concentrate the organic matter.

Autooxidation used by Riley et al. (3616) on wood hydrolysis waste showed promise for complete treatment of the waste water. Experiments using only mild autooxidation still required the waste to be diluted 1:90 before biological treatment. Temperature and the partial pressure of oxygen controlled the reaction rates. High pH wastes were biologically treatable (4915) although less oxidation occurs at these pH's. Davis (884) found an experimental trickling filter unsatisfactory for the treatment of a sulfite mill waste and it was abandoned. However, an experimental biofilter reduced the BOD of the impounded waste by 30%, removing about 2.1 lb BOD/yd^3/day (7.8 lb BOD/1,000 ft^3/day). Lebo and Hassler (2661) indicated that laboratory investigations of integrated pulp and paper mill wastes were amenable to both activated sludge and biological filtration. Subsequently, pilot scale, two-stage trickling filters were shown to give a total reduction of more than 65%. Irwin and French (2235) reported experiments on felt paper mill effluent which indicated that treatment in lagoons would not be practical and chemical coagulation of effluent would be expensive and ineffective. Based on pilot percolating filter plant data, a full-scale filtration plant with recirculation was built; this treatment reduced the effluent BOD to less than 50 mg/l.

Contrary to the above results (2235), Gehm (1443) in 1957 stated that percolating filters have not yet been proved to be effective in the removal of BOD, but modifications of the activated-sludge process have shown promise. Ten years earlier, Holderby (1977) was so convinced of the effectiveness of biological filtration for the treatment of sulfite waste liquors that he concluded it had greater possibilities of development than treatment by the activated-sludge process.

Recently, Wheatland (4698) reviewed both the biological filtration and activated-sludge process as they were applied to the biological treatment of waste waters from paper and board mills. Two-stage treatment by an activated-sludge unit and biological filtration was used by Ganczarczyk (1403), Gellman (1449), and Nowacki and Pilotek (3206). After investigating several methods including chemical coagulation, biological filtration, and activated-sludge processes, lagooning and filtration through fly ash, the activated-sludge process was chosen by Palladino (3277) for reasons of economics, efficiency, and ease of operation. Ratliff (3508) found that neither activated sludge nor biological filtration was satisfactory for the treatment of wastes from the manufacturing of jute liners, chip boards and corrugating materials from waste paper. He concluded that a circulating lagoon was required for the treatment of this particular paper waste to reduce the BOD. However, the effluent from the lagoon required further treatment which was obtained by biological filtration. After studying the effect of activated-sludge process and biological trickling filters on wood fiber waste, it was noted (2541) that the best results were obtained with the "P-method of Magdeburg." In the presence of iron salts this method gave a reduction of greater than 70% BOD_5 and 50% permanganate value after six hours of aeration with a sludge concentration of 2.2 kg/m^3 (6.3 lb/yd^3).

Typical of many of the papers presented on the effectiveness of activated sludge or trickling filters was that of Morgan (3093) in which he reported that an influent BOD of 414 mg/l and suspended solids of 1,602 mg/l were reduced to: (a) 169 and 1,600 mg/l after six hours' aeration which had 12.5 mg/l sodium nitrate added; and (b) 358 mg/l BOD with no nitrate added and 295 mg/l BOD where nitrate was added after passage through a six-foot deep percolating filter. The effects of thermal loading were studied on activated sludge and synthetic medium trickling filter-cooling tower combination units and evaluated by Burns and Eckenfelder (538). These tower units were a feasible addition to existing waste treatment facilities, but due to the inhibitory factors of paper mill wastes there was only slight improvement in the final effluent BOD.

POST-TREATMENT AND EFFLUENT QUALITY

Post-treatment required by a trickling filter operation for the treatment of paper mill effluent was investigated by Gehm and sponsored by the National Council for Stream Improvement, Inc. (1441), where by alternative processes the uses of effluent were explored. Grant (1537) reported that waste waters from paper mills which do not make their own pulp can be treated satisfactorily by flotation, settling in open beds, or filtration. Sheen (3976) emphasized that the presence of color, toxic compounds, and substances which would cause taste in a municipal water supply must be dealt with using mechanical, biological, and/or chemical methods. Chemical clarification plus organic removal by percolating filters alone and in conjunction with the activated-sludge process have been used.

Typical of the many patents on treating paper mill wastes was that issued to Metallgesellschaft (2982). Ferrous or aluminum sulfate in the presence of activated sludge or a mixture of similar organisms was used as a post-treatment to remove the colloidal organic material. Gehm and Gellman (1444) observed successful operation of paper mill effluent treatment by biological filtration followed by the activated-sludge process, with the activated sludge returned to the influent of the filter. Some paper mills found it economical to transport their cooking liquor waste to other locations to be treated, as noted by Krussman (2579). The treatment consisted, typically of alum and Separan® 20* coagulation, sedimentation, biological filtration, and chlorination of the effluent before discharge to the receiving creek. Burns and Eckenfelder (538) used two fabricated media trickling filters ahead of an existing activated-sludge plant to take advantage of the rapid BOD reduction and cooling effect. Biological trickling filtration as post-treatment of anaerobic digestion was not efficient for single filtration; however, double filtration on a laboratory scale proved desirable, according to the results obtained by Roznoy (3708). Clarification was a common post-treatment procedure (3093).

SPECIAL OPERATIONAL PROBLEMS

In determining the efficiency of biological processes treating paper mill effluent, Kalbe (2366) found that the 5-day BOD test (as determined by the dilution method) could give misleading results; but the Warburg method gave an accurate picture of the course of decomposition of the organic compounds. Horlock (2033) discussed the application of the BOD test to pulp and paper manufacturing wastes and stressed the need for a standard synthetic dilution water to measure the effects of treatment by percolating filters and by the activated-sludge process and anaerobic fermentation. The Department of Scientific and Industrial Research (England) has been active in developing tests to evaluate the performance of various unit operations (5175).

---

*Registered trademark of The Dow Chemical Company.

Sciver (3926) observed that suspended solids in paper mill effluent usually made sedimentation more difficult; however, cases have been experienced where paper solids acted as coagulants. A breakdown of treatment costs using the activated-sludge process, trickling filters, lagooning, and land disposal for the treatment of paper mill effluents was prepared by Caron (621). Research on the development of treatment systems to handle waste from the sulfite process was financed and supervised by the National Council for Stream Improvement (5391) to provide operational and design data on trickling filters and stream aeration. This sponsored work was based on laboratory experience of the Wisconsin Sulfite Pulp Manufacturers' Committee on Waste Disposal (5662).

A patent was issued to Neil (3155) on a specially operated filter which had vertical surfaces and retainers which accumulated solid material such as from pulp effluents. A temporary operation was used during the period of reconstruction in Germany after World War II where paper factory waste waters were discharged directly to the sewerage system after coagulation (1811). Typical of the uses of sludge generated by the treatment of waste waters from paper factories was that described by Lesenyei (2685), where the sludge was mixed with peat and used as compost at the percolating filter treatment plant. Studies in Japan (2163) indicated that the treatment of calcium-based acid sulfite process waste water by biological filtration and the activated-sludge process was effective in removing organic matter, but not effective for the removal of lignin. Investigations on the removal of furfural from wood hydrolysis plant waste waters demonstrated that biological filtration would completely oxidize this material (1033).

Critique

Considerable work was published on the use of biological trickling filters for treatment of pulp and paper related waste waters. The evidence was presented repeatedly that with certain pretreatment, e.g., pH and suspended solids, the waste was biologically treatable. Several papers were prepared on the advisability of using trickling filters versus other systems such as the activated-sludge process. Data were not available to document the reasons for the decision of the selected treatment based on economics. Performance information was available and could be compiled and reduced for common comparison. Trickling filters used in combination with the activated-sludge process and other systems were reported several times with essentially the same conclusion, that it was a desirable approach.

This industry should be congratulated for its efforts to provide resources and emphasis on clean water through the formation of agencies like the National Council for Stream

Improvement. Cooperative efforts of these agencies and other industries to develop treatment systems and measuring techniques have provided the basis for contemporary efforts. Methods other than biological treatment have been used, but the large quantities of water required in this industry necessitate the most economical form of treatment. Often this economic criterion determined that biological treatment, and specifically trickling filters, alone or in combination, is the pollution abatement answer.

SECTION XXIX

RADIOACTIVE WASTES

General surveys have been sponsored by the Atomic Energy Commission (5578) to investigate design factors and behavior of unit operations dealing with the removal of radioactive isotopes. From this work, information was disseminated on many aspects of radioactive waste disposal. Pazdernik (3317) and Ruf (3776) reviewed the general literature available on the treatment of radioactive wastes, such as that from the waste waters from laundries, and concluded that both activated sludge and biological filtration were very effective.

The concentration of radioactivity throughout waste treatment facilities and the various unit operations were discussed by Kenny (2434) and it was found that very little adsorption of radioactivity by sewage solids occurred during primary sedimentation. Treatment by activated sludge or biological filtration partially sorbed iodine-131, cobalt-60, phosphorus-32, and carbon-14, while sodium-24, potassium-42, bromine-82, sulfur-35, strontium-89 and 90, and radioactive tritium passed straight through. Investigators such as Newell (3178) and Colas (753) in 1950 studied radioactive waste pollution and described methods of treatment, such as ion exchange, distillation, evaporation, sand filtration, biological filtration, absorption by volcanic ash, adsorption, lagoon treatment, chemical coagulation, activated sludge, and ultimate solids disposal. Radioactive waste treatment facilities were also described by Sumiya and Muramatsu (4268) to include biological filtration with other unit operations.

Pettet (3355) and Brown (499) recognized radioactive waste disposal to be a significant problem and established special groups to study and handle the waste and suggested alternative methods of treatment. Newell et al. (3176, 3177) characterized radioactive contaminated laundry wastes as containing soap, synthetic detergents, citric acid, and lint, and had a BOD of 200 to 600 mg/l, and an average alpha count of 1,000 up to 20,000/min/l. Pilot plant studies indicated that plutonium can be removed from waste waters by coagulation with ferric chloride and lime, followed by slow filtration through sand (3176).

PRETREATMENT REQUIRED

A fundamental paper was presented in 1951 by Belcher (248), which dealt with the theory of adsorption of radioactivity by suspended solids and the relationship of sewage treatment processes for the removal of five commonly used radioisotopes. Later, Eden et al. (1100) also described similar experiments and their results to remove common radioisotopes.

The Atomic Energy Commission built its first full-scale plant for radioactive waste disposal near Idaho Falls, Idaho (327). The radioactive waste waters were mixed with domestic sewage in the ratio of 1:10. Treatment was by primary sedimentation and biological filtration with continuous recirculation of the effluent in the ratio of 5:1. Secondary sedimentation was also used and the chlorinated effluent disposed underground.

The effect of strontium-89 was measured by Ilyin (2166) who observed that the maximum concentration of the isotope in the biofilm was 1×10^{-5} c/kg of raw weight. This amount of isotope did not affect the biochemical activity of the microorganisms or increase the weight of film. Similarly Zhogova (4861), during experimentations with polonium-210 and strontium-90, did not observe any evidence that the presence of radioactive contaminants had any harmful effect on the biofilm or on the purification of sewage.

EFFICIENCY OF TRICKLING FILTER APPLICATION

The U. S. Atomic Energy Commission has published reports (5577) dealing with the effectiveness of sewage treatment processes for the removal of radioisotopes. Studies on activated-sludge process and biological filtration were described for different isotopes. The removal of fission products by biological filtration varied from 70 to 85% and was unaffected by recirculation of the effluent or by variations in BOD loading from 750 to 3,090 lb/ac-f/day (7.2 to 71 lb BOD/1,000 ft^3/day) and hydraulic loadings of 2.2 up to 12.8 mgad (50.6 to 294 gal./ft^2/day). Chemical and biological techniques were investigated by Newell et al. (3177) and operation of two-stage percolating filters with a recirculation ratio of 6:1 gave satisfactory results with a BOD being reduced by 90% and low rates of application at 0.3 mgad (6.9 gal./ft^2/day) produced the required activity removal. Dobbins (984) demonstrated that 90% removal of mixed fission products from radioactive laundry wastes contain detergents and organic acids were removed by biological filtration. Two-stage filtration removed about the same amount of activity that single stage filtration did when the total volume of the filter medium was the same. A percolating filter packed with pozzolana medium was effective (4822) in the removal of radioactive waste waters. After passage of these waters through the bed four times, 75% of the original radioactivity was fixed on the bed while only 7% was removed with the sludge.

Iodine-131 was added to settled crude sewage, and, as the rate of application increased (632) from 2 to 6 mgad (46 to 138 gal./ft^2/day), BOD removal decreased from 92% to 75%; however, at the rate of 2 mgad (46 ga./ft^2/day) 85% of the iodine-131 was removed in 6-foot deep filters.

Analysis of the biofilm indicated a concentration of iodine-131 to give counts of 10^6/min/g of slime which contained about 4.5 μc/g dry weight. Percolating filters were used at the Brookhaven National Laboratory (5576) to remove radioactive substances from laboratory waste waters. Removal efficiencies were high enough so that only 10% of the phosphorus-32, 12% of iodine-131, 1% of strontium-90 - yttrium-90, and 2% of mixed fission products passed through the filter. This removal was interpreted as an average reduction of 59% in the activity of the waste waters from the laboratory.

COMPARISON OF OTHER METHODS OF TREATMENT

The efficiencies of biological filtration, activated sludge, and oxidation ponds for removing radioactivity from waste waters were compared by Kaufman et al. (2385) in 1956. In all cases, they observed that the uptake of radioactivity was inversely proportional to the concentration of the isotopic carrier. The activated-sludge and biological filtration processes were both effective in the removal or radioactive materials from contaminated laundry waste (4715). Liebmann (2715) used low and high rate percolating filters and activated-sludge plants to remove radioactive substances and indicated that the pH values, periods of aeration, and other biotic factors were important in providing conditions for sorption and subsequent removal.

Eden et al. (1100) determined the efficiency of biota to remove radioisotopes from water and specifically commented on the performance of slow sand filtration and the activated-sludge process. They concluded that for the elements investigated, which were iodine-131, strontium-90, ruthenium-106, cerium-144, and plutonium-239, slow sand filtration would be suitable only for removal of radioactive cerium and possibly for plutonium, and chemical methods were more satisfactory than activated sludge. Radioactive waste waters from laboratories in Belgium had an activity of less than 10^{-3} mc/ml and were treated by two-stage chemical coagulation followed by adsorption, according to Dejonghe (913). Radioactive wastes with activities between 10^{-3} to 1 mc/ml were treated by evaporation and/or filtration through brown coal. Sanitary sewage and decontaminated radioactive waste waters were treated with sodium phosphate and passed through percolating filters. This total treatment removed an average of 85% of alpha activity and 75% of beta activity (913).

POST-TREATMENT AND EFFLUENT QUALITY

Subsurface disposal (327), storage (3178), and other (753) post-treatment procedures have been used to protect the environment from radioactive wastes. The effect of the radionuclei discharge to the sea and receiving bodies of water was discussed in considerable detail by Kenny (2434). He reported in June, 1957, on the properties of radioactive materials and the effects of alpha, beta, gamma, and X-rays on human beings.

It was recommended by Wiederhold (4715) that two-stage operation or final coagulation of the effluent should be employed to remove residual activity even though biological filtration removed most of the radioactivity. Procedures such as this have been required, according to Newell (3177), to reduce the plutonium activity in the discharged waste to be less that 70 counts/min/l which was accomplished by chemical-biological treatment. Radioactive tritium passed straight through the treatment process (2434), as did cesium-134 and rubidium-106 (1489). These failures of biological systems required additional post-treatment.

SPECIAL OPERATIONAL PROBLEMS

Fowler et al. (1319) determined the conditions of adsorption of rubidium-86 on biological percolating filters and they observed that the adsorbed radioactivity was associated with the biofilm growth. More activity was adsorbed at the one-foot depth than at the surface of the filter. It was concluded that the biofilm was important in the adsorption of radioactive isotopes which, in the case of rubidium-86, was not irreversible. Versene®*, the disodium salt of ethylenediaminetetraacetic acid, was found to have an adverse effect on the removal of fission products by both activated sludge and biological filtration due to its chelating or complexing abilities (5577). The relationship of pH and period of aeration were considered to be a problem (3776), and alternative methods and treatment experience were related. After initial adsorption of the radioactive material, the adsorption rate dropped off (1489), and cesium-134 and rubidium-106 were not handled adequately by biological treatment.

Critique

The literature indicated some advantage in using biological filtration for the removal of radioactive wastes. The treatment of these wastes, which is a relatively new industry, was reported to involve chemical, physical, and biological waste treatment methods. Evidence was given of the adsorptive capacity of the biofilm for several radioisotopes. Problems developed from relying on this adsorptive capacity for certain elements which were not permanently removed from solution.

---

*Registered trademark of The Dow Chemical Company.

Literature other than that reviewed here has shown considerable interest in the removal of radioactive materials from waste effluent. Investigators such as C. P. Straub and R. Eliassen have reported extensively on the treatment of low and high level radioactive waste. This literature review serves the purpose of demonstrating investigators' awareness of the adsorptive capabilities of biological filtration. Generally, it has been shown that biological filtration requires pretreatment for most radioactive wastes. There are many radioactive wastes at such high level discharge that methods other than biological filtration must be used.

SECTION XXX

TANNERY WASTES

The significance of tannery waste disposal problems was noted by the formation of committees (5565) charged with the responsibility for several investigations dealing with storage, sediment, filtration, chemical treatment (if necessary), and secondary sedimentation. This committee recommended in 1931 that final filtration through six feet of coke should be included after pretreatment by chemical precipitation. Caution was expressed that logwood should be used as the filtering medium because acid in the waste water reacted with the iron in the coke to color the solution blue-black. Wastes, which were categorized by Russel (3787) as tannery wastes, were formerly discharged untreated to receiving bodies of water, but, according to Taylor (4328), were also combined with the municipal waste water and treated by biological filtration.

Reuning (3562) reported that tannery waste waters contained lime, hair, and hide particles, and were very caustic and highly colored. Treatment was generally based on results of experiments in Pennsylvania between 1924 and 1930 (5565) and consisted of coagulation, sedimentation, and biological filtration. Under difficult situations, the colored water was evaporated or treated in lagoons. A combined tannery and municipal waste was characterized by Eddy and Vrooman (1088) to be warmer than domestic sewage and to possess more organic material. Kalibina (2367) reported in 1930 on experimental work dealing with the treatment of tannery wastes by the activated-sludge process, aerated contact filter, and percolating filter. He concluded that biological examination is a rapid means of judging the quality of a purifying plant and that the concentration of tannery waste water appeared to have little influence on the purifying effect.

During a forum on industrial waste and related problems in 1950, McKee and Camp (2920) outlined particulate material, high alkalinity and hardness, hydrogen sulfide formation, and discoloration of receiving streams as being primary problems of tannery wastes which required treatment. In an early effort to evaluate or characterize the relative strength of tannery waste, McGowan (2911) developed an indexing system based on oxygen consumption which was related to the operation of biological filtration.

Tannery wastes were characterized by Diénert (972) to be 778 m^3 (210,000 gal.) of washing water, 816 m^3 (220,000 gal.) of waste water from the "limes," 531 m^3 (140,000 gal.) of tanning water, making a total volume of 2,325 m^3 (614,000 gal.) of waste water a day for 82,000 kg (90 tons) of skins treated in a month. Rosenthal (3692) and Power (3450) discussed problems of tannery waste treatment and listed the characteristics of the waste as having a pH of 11.8 and a total alkalinity of 1,100 mg/l as calcium carbonate.

Preceding page blank

Parker and Watkins (3299) described the waste treatment plant at Middlesborough, Kentucky, as a combined municipal and tannery waste-treatment facility and characterized the tannery waste as containing 8,500 mg/l total solids, 1,700 mg/l suspended solids, and 3,300 mg/l volatile solids with a BOD of 830 mg/l and an alkalinity of 1,155 mg/l. They calculated that the population equivalent of these wastes, based on suspended solids, was 20,700, and based on BOD was 15,500, but the actual population of the community was less than 12,000. One mgd tannery effluent was handled in conjunction with 3.5 mgd of combined domestic sewage and milk processing waste in a plant consisting of grit chambers, coagulation and sedimentation processes, standard and high-rate biological filtration followed by final sedimentation (1768).

PRETREATMENT REQUIRED

Allen (35) reported pretreatment devices, such as fine mesh screens, were installed at tanneries to remove hair and solid materials from the influent. In a combination plant, the tannery wastes were added to the sewage in a mixing chamber, the pH was adjusted, and further treatment was accomplished by a conventional trickling filter plant (3299). Morrison (3099) identified in 1911 that lime and tan liquors were mutually precipitable and that these combined solutions could be used to clarify other suspended matter in tannery effluents prior to biological filtration. Two chemical purification processes to handle tannery waste effluents were used by Génin (1453), but a physical process, such as decantation of filtration, for removing the precipitate was required. Based on laboratory studies, pretreatment using lime or alumina ferric dosed at 1 to 4 pounds/1,000 gallons removed most of the 25,960 mg/l of leather dressing colloidal material (1302).

An arrangement was reported by Hughes (2084) whereby tannery effluents were discharged to the municipal treatment plant after midnight and were subsequently treated in a separate settling tank prior to biological filtration. Aue (103) described a separate waste treatment facility which was used to treat tannery waste waters which involved flow equalization, chemical precipitation, and reduction of pH, after which the waste water was discharged to the municipal system where sedimentation and high-rate biological filtration were used.

EFFICIENCY OF TRICKLING FILTER APPLICATION

Eddy and Vrooman (1088) concluded that biological processes could treat tannery wastes and that covered percolating filters could be dosed at 1 mgad (23 gal./ft^2/day) following pretreatment at the tannery site to maintain 90% removal of suspended solids. Color was removed largely through the sprinkling filter and completely through the sand filter, but some inoffensive odor was retained. Clark (692) stated in 1910 that pretreatment with calcium hydroxide, followed by sand filtration, could remove 60% of the organic matter from tannery waste. Nemerow and Armstrong (3165) revealed the results of an industrial waste survey in New York where 22 tanneries had effluents contributing to the pollution of the receiving waters. The survey indicated (3165) that secondary treatment of the combined industrial and domestic waste was necessary to produce 65 to 97% reduction in BOD. Humphreys and Bailey (2089) studied the treatment of tannery waste alone and in combination with domestic sewage, and it was determined that biological filtration at a rate of 70 gal./yd^3/day could be sustained with trivalent chromium up to 30 mg/l without suffering a decrease in either BOD or permanganate demand efficiency.

A two-stage biological treatment plant was found (2978) to be particularly suitable for the treatment of tannery waste in Germany. The activated-sludge process combined with biological filtration produced satisfactory results as indicated by daily tests on BOD, permanganate demand, pH value and turbidity. The sewage disposal plant at Keighley successfully treated 4 mgd of sewage including a heavy trade waste (5017) of 900,000 gal./day of primarily textile and tannery wastes by conventional percolating filters. The final effluent contained an average of 35 mg/l suspended solids and 26 mg/l BOD.

In 1964, Gorecik (1520) investigated the effect of phenol occuring in tannery waste waters. He determined that for optimum removal of phenol (86.2 to 94.6%) not more than 2,000 grams BOD/m^3/day (125 lb BOD/1,000 ft^3/day) could be loaded on the Biofilter. Experiments on the purification of tannery wastes by chemical precipitation, primary filtration through cinders at a rate of 250,000 gal./acre/day, and secondary filtration through sand at a rate of 300,000 gal./acre/day were performed by Hommon (2002) in 1917. The suspended solids were reduced from 1,200 to 30 mg/l and the nitrogen was reduced from 70 to 25 mg/l.

COMPARISON TO OTHER METHODS OF TREATMENT

Processes which were reviewed by Chase and Kahn (662) and by Diénert (972) included straining and settling, followed by the activated-sludge process, filtration through crushed stones, filtration through clinker followed by a sand filter and other clarifiers. In 1960, Paszto (3308) carried out pilot plant experiments on tannery waste waters using sedimentation, chemical purification, biological filtration and activated sludge. He indicated that chemical purification was expensive, but a perfect solution to the problem. He concluded that biological filtration could be used only after 90% dilution of the waste water, while the activated-sludge process could be used after 60% dilution of the tannery waste with domestic sewage. Schwarz (3923) detailed pilot plant studies on combined treatment of heavily polluted tannery waste waters to demonstrate the waste to be more completely treated by the activated-sludge process than biological filtration, in agreement with Kubelka (2580). Kabakowa and Kalabina (2362) investigated the purification of tannery wastes by the activated-sludge process and slag contact tanks on a laboratory scale. They concluded that the best treatment was obtained in the activated-sludge system at 33% sludge and a non-putrefying product was obtained by oxidation in contact with brown coal after chemical coagulation.

However, biological filtration was noted (972) to give best removal treatment. Allen (35) constructed and operated a pilot plant which employed activated sludge and biological filtration operated in series and parallel plus alternating double filtration or recirculation of the effluent. He concluded that alternating double filtration was the best procedure.

Kubelka (2580) discussed the treatment of tannery waste waters by soil filtration, fish ponding, percolating filters, and the activated-sludge process. Primary sedimentation was necessary and treatment by the activated-sludge process was regarded as preferable to biological filtration. Soil conditions made land disposal impractical and fish ponds appeared possible, but were not tried. Thabaraj et al. (4346) made a comparative study of some 50 investigators' reports on the treatment of tannery effluents by trickling filter, the activated-sludge process and lagooning. Preliminary treatment, by mixing effluents from individual tannery processes, resulted in flocculation and particulate removal. No particular advantage was given to any treatment system and the advantages and disadvantages of each were identified. They concluded that the system choice would depend on local, economic, operational and environmental factors.

Gononian (1514) suggested that oxidation, chemical precipitation and filtration were required. Rohde (3671) described the Niers Process for the treatment of sewage with high percentage of waste waters from tanneries and textile mills. To purify tannery waste waters, a filtration gallery-type system, in which loosely layered granite stone was placed in a shallow channel, produced results comparable with that obtained in standard percolating filters, but further investigation was deemed necessary to determine the effect of various process factors on this system (4528).

POST-TREATMENT AND EFFLUENT QUALITY

Usual post-treatment was in the form of humus tanks, lagoons and chlorination. Anthrax was noted as being well under control. Merz (2980) described methods for treating tannery waste waters in East Germany which involved the removal of fat, sedimentation in lagoons, and sludge thickening, but tests were in progress in 1961 to determine the effect of biological treatment of the effluent in deep-bed percolating filters.

SPECIAL OPERATIONAL PROBLEMS

In 1950, Vrooman and Ehle (4565) discussed problems in treating the waste at Gloversville, New York, which contained a high proportion of tannery waste waters. As was later reported by Nemerow and Armstrong (3165), the existing waste treatment plant was overloaded and a pilot plant was constructed to determine the possibilities of digesting sludge which was obtained from the biological filtration process as well as the high suspended solids of the tannery waste.

Hofer (1973) reported, in 1910, that tannery waste in sewage was a detriment to biological purification and separate steps were required for its treatment. Allen (35) noted that the resistance to biological treatment of tannery waste water posed a difficult problem and made the cost of separate treatment prohibitive. Cohn (737) reported, in 1925, that filter flies appeared during the treatment of tannery wastes on biological filters at Norwood, Massachusetts. A dosage of 1,600 ppm chlorine was applied before the number of flies were appreciably reduced, but this also materially reduced the efficiency of the filters.

Critique

Tannery wastes were adequately reported to have characteristics of significant BOD and excessive suspended solids load. Experimentation dealing with several biological, physical, and chemical processes resulted in the publication of many reports. Biological filtration was shown to be effective, but papers show that situations arose where other systems, such as the activated-sludge process, were more efficient. The literature reflected good communication among investigators by the formation of responsible committees to sponsor aggressive research and development and to disseminate the results.

It appears from the literature that a reasonable approach to the treatment of tannery waste has been adequate pretreatment at the tannery site with discharge to a larger municipal treatment plant. Pretreatment at the site was the removal of suspended and colloidal solids, pH adjustment, and some roughing filter-type oxidation. These pretreatment steps have been shown to be necessary to dampen the extreme characteristics of tannery wastes arising from the curing, flushing, washing and soaking, unhairing, lime splitting, bating, pickling, degreasing, bleaching, fat-liquoring, and dyeing processes.

Biological filtration has not been used as extensively in this industry as in others reviewed. Inherent difficulties from the characteristics of the waste have relegated the treatment to lagoons and other low efficiency operations.

SECTION XXXI

TEXTILE WASTES

The problem of waste waters from the textile industry caused sufficient interest that associations were formed (4876) to investigate characteristics of waste waters and explore methods of treatment. Alkaline wastes (characteristic of textile wastes) posed a sufficiently difficult problem to investigators that the American Society of Civil Engineers sponsored (4915) research projects to investigate biological oxidation of alkaline wastes. It was concluded that these wastes could be treated biologically without neutralization although less oxidation would occur at high pH values (4915). Eldridge (1139), Pettet (3355), and Masselli et al. (2881) generally reviewed industrial waste treatment on municipal sewage treatment facilities and, in categorizing them, noted that textile wastes required complicated chemical treatment and their treatment with domestic sewage was not generally recommended. However, Porges et al. (3434) treated textile wastes at 24 mgad (552 gal./ft^2/day) with recirculation.

Wool scouring wastes were described by Wishart (4789) as difficult to treat, but with sufficient dilution were amenable to biological treatment. An increase in organic matter was to be expected due to contributions from cotton, flax, hemp, and jute bleaching wastes as well as caustic alkalinity. Rapidly putrefying silk wastes were treated adequately by chemical precipitation. Dyeing waste waters contained suspended material, and recoverable dyes, such as indigo, were removed at the factory while other dyes were subjected to chemical precipitation. Gibson and Wiedeman (1466) stated that textile wastes included caustic and soda ash, detergents and soaps, desizing wastes, acids, reducing agents, resins, and dyes.

Hart (1758) and Souther and Alspaugh (4117) concurred with other investigators that the characteristics of cotton bleaching and dyeing wastes were high alkalinity, suspended matter, color, and BOD. Dickerson (953) characterized cotton dyeing and finishing plant waste to have from 3,000 to 30,000 lb BOD/day with waste flows from 2 mgd to 15 mgd. A major source of the BOD came from the cornstarch used in processing the cotton which was washed away with hot water. Textile dye wastes were discussed by Nemerow (3163), in 1952, and categorized as direct dyes, sulfur dyes, vat dyes, acetate dyes, and naphthol dyes. The wastes were characterized as being alkaline with a high oxidative demand, rich in color, had an elevated temperature, and sulfur dye wastes were extremely toxic. Gauge (1429), in 1922, described the waste liquors from flax wetting to be dark yellowish-green liquids with offensive odors and acidic properties, which had less suspended matter and nitrogen than raw sewage. These liquors were suitably treated by

Preceding page blank

biological filtration after chemical treatment with calcium oxide and aluminum sulfate. Sharda and Manivannan (3969) categorized effluents from a viscose rayon factory as alkaline, viscose, acid sulfide, and sanitary. Combined waste treatment might be difficult, but physical and chemical methods in addition to biological filtration were recommended.

Grey (1581) described a sewage plant to treat textile wastes and domestic sewage. Treatment consisted of separate sewage and trade waste influents, screening and comminution, equalization and mixing, coagulation with alum, ferric sulfate, and lime sedimentation, and biological filtration followed by final sedimentation with sludge digestion.

Irwin and French (2234) and Lloyd (5290) reported that two-stage biological filters with recirculation following screening and sedimentation provided satisfactory treatment for felt mill and combined textile-sanitary effluents. However, Gibson (1466) suggested that recirculation or organic load had little to do with the BOD filter efficiency of trickling filters and the activated-sludge process. Disposal of silk mill wastes was described by Geer (1439), based on experimental studies of sand filtration, various forms of settling, and biological filtration. Later, a biofiltration plant for silk mill wastes was operated by Jenks (2308) on the high-rate filtration principle. The high standards set for the effluent from cellulose and viscose artificial fiber plants caused Munteanu (3124) to build pilot plants incorporating physical, chemical, and biological treatment, both by filtration and the activated-sludge process, to develop data necessary for the design of full-scale plants.

Textile wastes were treated adequately on plastic media biological filtration systems which made activated-sludge tanks and other conventional methods impractical (98). Biggs (326) reviewed the literature and the capabilities of biological treatment and required pretreatment for handling of textile wastes and commented, specifically, on the application of plastic media biological trickling filters. A discussion (5196) on the use of plastic media biological trickling filters to provide economical and satisfactory treatment of textile wastes emphasized a roughing filter in congested areas of production facilities or waste treatment plants requiring rapid removal of high oxygen demand.

PRETREATMENT REQUIRED

Pretreatment was necessary, according to Smallhorst (4055), for the treatment of cotton finishing plants using ferric sulfate and lime to treat strong sulfur dye wastes as well as copperas and lime. Chemical treatment similar to present methods was used (5423) in the early 1900's such as lime and ferrous sulfate, followed by percolating filters and humus tanks. Flue gas was used (1758) to lower the pH of bleaching waste water as preliminary treatment. Textile waste waters at Russian installations were treated (3871) by similar methods of chemical precipitation followed by biological filtration. Treatment was commonly reported (953) to be in the form of chemical precipitation or biological oxidation, using combined percolating filters and the activated-sludge process. Textile effluents were reported by Kehren (2420) to be successfully treated by chemical precipitation using iron turnings, followed by sedimentation and biological treatment in percolating filters or the activated-sludge process to provide an acceptable effluent.

The replacement of organic acids with mineral acids in various dye processes was suggested by Snyder (4093). Preliminary treatment suggestions were made by Horton and Baity (2037) to reduce the volume of waste and recover by-products at the waste source. Anaerobic digestion of wool-scouring wastes was used (2631) prior to discharge of mill effluent to sewage works, where further biological treatment by filtration was accomplished. Equalization of synthetic fiber waste by admixture with domestic sewage and cooling water, followed by additional biological treatment, was outlined by Singleton (4039). McCarthy (2901) reported on methods of preliminary treatment to handle wool-scouring liquors, such as steam stripping and chemical addition. By diluting the waste waters from treating flax waste liquors to 1% with river water, it was possible to treat them by biological filtration (3226).

EFFICIENCY OF TRICKLING FILTER APPLICATION

McCarthy (2900) estimated that the waste waters from wool dyeing had a BOD of 0.25 to 1.0 lb/100 lb of wool dyed, and could be treated by biological filtration after dilution to produce 90% BOD reduction. With recirculation of the effluent, loads of 5,000 lb BOD/ac-f/day (115 lb BOD/1000 ft^3/day) were reduced by 89%. Waste waters from a desizing process contained digested sludge residues and exerted a total BOD of 3,000 lb/day in combination with other plant waste (4093). Biological filtration was shown to be effective for 75 to 80% removal of this BOD. By diluting with river water to the point that 1% of the flax waste existed (3226), treatment was accomplished on acclimatized biological filters which were loaded at about 500 lb BOD/ac-f/day (11.5 lb BOD/1,000 ft^3/day) and produced 57 to 72% removal which, after 35 days' operation, was raised to 70 to 90% BOD reduction. Chemical pretreatment significantly removed color from textile dye wastes and, when followed by biological filtration, the BOD was reduced by at least 86% and the color by 83% (3163).

Husmann (2149) found that waste waters from a textile mill, which included waters from bleaching and dyeing, could be treated on percolating filters without the addition of sewage, but with a recirculation ratio of 3:1 to reduce an influent BOD of 440 mg/l to 107 mg/l. Seasonal acclimatization was demonstrated by Petru (3341) to be effective in purifying retting waste in which the effluent improved as the retting season continued. Dahlem (854) treated waste waters from dyeing and bleaching plants by biological filtration with recirculation even though the pH was at times 12 to 13. Effluent recirculation at 3:1 produced 75% removal of oxygen demand. Biological filtration with recirculation at 1:1 of the effluent was used for treating cotton curing wastes, and when operated with alternating double filtration a BOD reduction of 95.7% was achieved (5289). Alternating double filtration (4039) was effective in improving the quality of effluent from synthetic fiber manufacturing waste treatment plants.

With the technique of intermittent filters following percolating filtration, Bogren (384) was able to reduce the BOD by 92.7% and the suspended solid by 99.6% in textile waste waters He also removed 75% of the BOD from cotton finishing wastes, in agreement with Dahlem (854). Removal of 58% of the BOD and 45% of the color was achieved by Souther and Alspaugh (4114) on a high-rate biological trickling filter treating a composite dye house, bleaching, finishing, mercerizing, and color shop wastes mixed with domestic sewage. Combined treatment using high-rate filtration and activated sludge (4114) resulted in 93% BOD removal and 50% color removal which was verified later by Souther and Alspaugh (4115, 4116). The biological filtration after sedimentation removed 73% of the BOD at a pH of 8.5, and 58% at a pH of 10.5 (4115).

A treatment plant was described by Brown (491) which removed 82.6% of the BOD from a mixed waste containing 60% textile waste waters and 40% domestic sewage via processes involving pH adjustment, primary sedimentation, and two-stage biological filtration, followed by humus tanks. Walter (4592) studied the combined treatment of sewage and textile waste waters and the effect of high pH on the performance of roughing percolating filters. Loadings of 3,000 to 6,000 lb BOD/ac-f/day (69 to 138 lb BOD/1,000 ft^3/day) were removed about 60% by biological filtration. The filter reduced the pH of the waste and, since little reduction in BOD was achieved by settling plus the necessity for second stage filtration, an intermediate clarifier was not justified (4592). Nutritional deficiencies and other biotic factors were investigated by Oldaker (3227), and it was determined that the optimum BOD removal occurred when 1 lb of phosphorus was added for every 98 lb of BOD removed. An 8% increase in BOD reduction was obtained by reducing the pH from 11.5 - 12 to 7.5. Kilgore and Sawyer (2477) supported these findings in separate studies of nitrogen and phosphorus requirements.

COMPARISON OF OTHER METHODS OF TREATMENT

Milligan (3010) discussed the laws of the Pennsylvania Sanitary Water Board concerning the effect of textile industry effluents and treatment on biological filters with recirculation of effluent, and final chlorination was preferred to chemical coagulation. After comparing performance of chemical coagulation, biological filtration, and lagooning, Williams and Hutto (4738) constructed pilot plant aerated lagoons to treat waste waters from synthetic fiber and other textile mills which produced reductions in BOD of 75 to 80%. Souther and Alspaugh (4116, 4117) recommended treatment similar to that of other investigators and pointed out advantages and disadvantages of processes such as lagooning, chemical treatment, coagulation, biological treatment by both percolating filters and activated sludge. Additional flexibility was designed into plants by Grey (1581), which allowed chemical treatment for neutralization and disinfection, as well as the addition of the influent waste waters at several points throughout the treatment plant.

Gotaas (1521) discussed textile wastes containing unstable organic matter and toxic constituents and indicated that the activated-sludge process removed color better, but was less resistant to shock loads and to toxic substances than trickling filters. Horton and Baity (2037) used the activated-sludge process and biological filtration for treatment of textile waste and sewage mixtures with the usual process limitations. Nicholas (3183) successfully operated a Kessener brush aeration unit which provided satisfactory treatment on a combined waste flow containing waste from the manufacture of tweed and woolen garments. This waste did not require preliminary treatment and this aeration unit was chosen in preference to chemical coagulation and to high-rate biological filtration.

According to Oldroyd (3229), alternating double filtration on a laboratory scale was effective on the treatment of textile wastes when the primary filter was loaded at 400 gal./yd^3/day, while the diluted waste was applied to the secondary filter operating with recirculation at 500 gal./yd^3/day. This system was compared to two-stage high-rate filtration without recirculation. However, both systems ponded. He concluded that the slightly better results of alternating double filtration were not worth the added capital investment and operational requirements over two-stage operation with recirculation at a constant rate.

POST-TREATMENT AND EFFLUENT QUALITY

Meyer (2987) recommended the use of spray irrigation of flax retting waste waters in Germany even though biological filtration had been used successfully for years under lightly loaded conditions. Fleming (1294) noted that woolen mill wastes were treated with combined domestic sewage on percolating filters which produced a sludge used as a fertilizer. McCarthy (2901) noted common use of backwashing filters and high dilution of effluent to reach an acceptable performance level. Reductions in hydroxyl alkalinity, BOD, total settleable solids, color, and temperature of the waste were accomplished successfully by lagooning the textile waste waters (4117).

SPECIAL OPERATIONAL PROBLEMS

A conventional activated-sludge plant treating a combination of sewage and textile waste waters in North Carolina became overloaded and was operated only as a chemical precipitation plant (839). A volume of 11 mgd, 40% of which was textile waste, was treated. Before designing a new plant, pilot plant studies were made and it was concluded (839) that an effluent BOD of 50 mg/l could be obtained by a two-stage biological treatment if the pH were controlled to less than 9.5. A harmful characteristic of textile waste was reported by Ingols (2219) to be the large quantity of detergents imparted to the sewers from washings which interfered with sedimentation and resulted in overloading percolating filters.

Horton and Baity (2037) discussed problems of treating combined textile and domestic sewage due to the changes in character of the sewage as it reached the treatment plant. Difficulties in treatment of waste waters from cotton kiering, cotton bleaching, and pulping of rag and rope by two-stage high-rate percolating filters were attributed by Kilgore and Sawyer (2477) to nutritional deficiencies. The requirements for nitrogen and phosphorus of the different wastes varied from 4.7 to 7.4 lb of nitrogen and from 0.36 to 1.25 lb of phosphorus per 100 lb of BOD removed, with similar needs for activated sludge and biological filtration. Oldaker (3227) generally agreed with the nutritional demand.

Souther and Alspaugh (4117) stated that the volume of waste water which could be treated biologically without preliminary treatment was limited by the hydroxyl alkalinity rather than by the pH value. According to Petru (3340), acclimatization of filters which were to treat concentrated waste waters, such as that from flax retting, is an operational requirement. The maturing of a filter is shown by a steady decrease of BOD and an increase of pH value.

Critique

Waste waters arising from the production of textile goods have been reported in many texts, e.g., "The Treatment of Industrial Waste," by Besselièvre (308), in conjunction with biological trickling filters. Textile wastes have been generally considered to be highly alkaline, contain high dissolved organics and suspended solids, be of an elevated temperature and colored in various degrees. Several different types of chemical, physical, and biological waste treatment have been employed. Since the development of synthetic fibers, which have wastes quite similar to those from the chemical industry, most treatment schemes have been considered.

Wastes arising from the production of cotton, wool, silk, synthetic fibers and other materials have been treated by biological filtration with various degrees of success. Pretreatment to establish the proper pH range and to remove suspended solids was frequently emphasized. Additional components in the textile wastes, such as detergents and toxic dyes, complicated the problem of waste treatment.

It would appear, based on this review, that adequate treatment of textile wastes can be achieved by biological filtration in combination with other treatment processes. These processes would involve pretreatment, not only in the form of pH control and suspended solids removal, but also in cooling and equalization. Biological filtration operated in series with other processes, such as the activated-sludge process, has been shown to be successful for the treatment of these difficult wastes. Low capital investments were spent for lagoon waste treatment, which was often used instead of biological filtration.

The literature reflected excellent communication among investigators. This may have been due to the formation of trade associations which explored methods of treatment and sponsored research and development to characterize waste waters and to propose alternative methods of treatment. Waste waters from similar production facilities had effluent characteristics that were correspondingly similar. Performance results agreed well with independent investigations on similar wastes. Trends similar to those observed for tannery waste treatment were noted in this area, e.g., for several years, reports were submitted which dealt with the difficulties of treating textile waste combined with domestic sewage. With the construction and operation of newer facilities, data were made available resulting in further process modifications. These modified plants were operated under several different conditions to optimize plant efficiency. Biological filtration was shown to be useful for the partial treatment of textile wastes, provided sufficient pretreatment was included in the design.

SECTION XXXII

ACKNOWLEDGMENTS

The following groups and sources aided in the development and completion of this review.

The staff of The Dow Chemical Company's Technical Library.

Mrs. Clementine Moore, of the National Environmental Research Center Library, located in the Robert A. Taft Sanitary Engineering Building, Cincinnati, Ohio.

Mr. Edwin D. Posey, of the Civil Engineering Library, Purdue University, Lafayette, Indiana.

Chemical Abstracts and Water Pollution Abstracts.

Messrs. D. G. Parker, K. F. Spear, J. W. Pollack, E. B. Albright and M. B. Ettinger, and Dr. S. L. Daniels made contributions to the bibliography and to this review under the guidance and leadership of Dr. C. H. Thompson, who compiled the rough draft. Dr. R. S. Karpiuk and Mrs. Isabel H. Carr reorganized and edited the rough manuscript to its final form. Mr. M. E. Arnold gave valuable assistance in reorganizing and editing the references. The sections on "Ecology" and "Bacterial and Viral Removal" were technically edited by M. B. Ettinger, J. J. McDade and J. N. Tadman. Ms. Karen Anderson, Helen Blank, Loretta Demers, Virgie Fisher, Margo Hardy, Neva Harrison, Vera Hart, Kim Short, Jean Shuler, Sharon Tomczak, Ann Wisniewski, and Carolyn Wyse provided the massive secretarial support under considerable pressure of an approaching deadline.

Preceding page blank

☆U.S. GOVERNMENT PRINTING OFFICE: 1972 484-487/311 1-3

SELECTED WATER RESOURCES ABSTRACTS

INPUT TRANSACTION FORM

1. Report No.

2.

3. Accession No. **W**

4. Title A LITERATURE SEARCH AND CRITICAL ANALYSIS OF BIOLOGICAL TRICKLING FILTER STUDIES. VOL. I AND VOL. II

5. Report Date

6.

7. Author(s)

8. Performing Organization Report No.

9. Organization The Dow Chemical Company
Functional Products and Systems Department
Midland, Michigan 48640

10. Project No. 17050 DDY

11. Contract/Grant No. 14-12-474

13. Type of Report and Period Covered

12. Sponsoring Organization EPA, Water Quality Office

15. Supplementary Notes

16. Abstract

A compilation, review and critique of the literature on biological trickling filter studies and related pollution abatement processes have been made. Volume I, the literature review and critical analysis, is divided into: (a) Introduction, Definitions, History and Background Theory of the Trickling Filter Process; (b) Plant Design, Materials of Construction, Operation, Maintenance and Performance; (c) Trickling Filter Research and Development Approaches, Ecology, and Patents, and (d) Applications of Trickling Filter to Specific Industrial Wastes. Volume II is the bibliography of 5,565 references. Based on the review, several general conclusions were drawn. There is no well-defined theory of design and operation. Much published work was redundant, and European efforts were not readily accepted in the United States, and vice versa. The literature reflects cycles of interest in trickling filters. The value of much of the early work was ignored. Solutions to complex pollution problems will be made by industry strongly supported by local, state, and Federal governments. The filter will be used in high efficiency, modern wastewater treatment plants. The process is not applicable to all pollution problems, but its shock survival capabilities and rapid flow-through time are definite advantages which cannot be overlooked in any design of a waste treatment facility.

17a. Descriptors *Review of trickling filters, *Bibliography, *Biological filters *Percolating filters, *Sprinkling filters, *Biofilters, *Theory, *Construction, *Operation and maintenance, *Performance, *Research and development, *Ecology, *Patents, *Industrial wastes.

17b. Identifiers

*Aerobic treatment, *Biological treatment, *Filtering systems, *Pollution abatement, *Treatment facilities. Application of trickling filters to brewery and distillery, chemical, gas and coke plant, food processing, institutional and military, laundry and cleaning, meat and poultry, metal working and production, milk processing, pharmaceutical and fermentation, pulp and paper, radioactive, tannery and textile wastes.

17c. COWRR Field & Group 10F, 05D

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

Abstractor Robert S. Karpiuk

Institution The Dow Chemical Company